

Thoracic Size-Selective Sampling of Fibres: Performance of Four Types of Thoracic Sampler in Laboratory Tests

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Received 14 October 2004; in final form 21 January 2005; published online 24 March 2005

The counting of fibres on membrane filters could be facilitated by using size-selective samplers to exclude coarse particulate and fibres that impede fibre counting. Furthermore, the use of thoracic size selection would also remove the present requirement to discriminate fibres by diameter during counting. However, before thoracic samplers become acceptable for sampling fibres, their performance with fibres needs to be determined. This study examines the performance of four thoracic samplers: the GK2.69 cyclone, a Modified SIMPEDS cyclone, the CATHIA sampler (inertial separation) and the IOM thoracic sampler (porous foam pre-selector). The uniformity of sample deposit on the filter samples, which is important when counts are taken on random fields, was examined with two sizes of spherical particles (1 and 10 µm) and a glass fibre aerosol with fibres spanning the aerodynamic size range of the thoracic convention. Counts by optical microscopy examined fields on a set scanning pattern. Hotspots of deposition were detected for one of the thoracic samplers (Modified SIMPEDS with the 10 µm particles and the fibres). These hotspots were attributed to the inertial flow pattern near the port from the cyclone pre-separator. For the other three thoracic samplers, the distribution was similar to that on a cowed sampler, the current standard sampler for fibres. Aerodynamic selection was examined by comparing fibre concentration on thoracic samples with those measured on semi-isokinetic samples, using fibre size (and hence calculated aerodynamic diameter) and number data obtained by scanning electron microscope evaluation in four laboratories. The size-selection characteristics of three thoracic samplers (GK2.69, Modified SIMPEDS and CATHIA) appeared very similar to the thoracic convention; there was a slight oversampling (relative to the convention) for $d_{ae} < 7$ µm, but that would not be disadvantageous for comparability with the cowed sampler. Only the IOM thoracic sampler tended to undersample the fibres relative to the thoracic convention. With the data divided into four classes based on fibre length, the size-selection characteristics appeared to be unaffected by fibre length for GK2.69, Modified SIMPEDS and CATHIA. Only the IOM thoracic sampler (with the foam selector) showed slightly lower selection for longer length classes of fibres. These results indicate that the tested samplers follow the thoracic sampling convention for fibres, and may be used to improve the quality and reliability of samples that are taken when there is likely to be significant background dust.

Keywords: fibres; sampling; size-selective; thoracic

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INTRODUCTION

There are important advantages which could be gained from applying some of the existing size-selective sampling methods (currently used for particles) to the sampling of fibres. In theory, this should

not prevent new measurements from being consistent with old measurements of fibre concentrations, and it should make new measurements more reliable, given suitable size-selective sampling instruments.

Fibre concentrations are currently measured using a standard method known as the membrane filter method, which is described in MDHS 39/4 (HSE, 1995), in Method 7400 (NIOSH, 1994) and in ISO 8672 (ISO, 1993a) for asbestos. For man-made mineral fibres, there are some significant differences in the way that the collected sample is processed, but the sampling procedures are essentially the same (WHO/EURO, 1985; HSE, 1988). In these methods, air samples are taken onto membrane filters in cowed sampling heads and the filters are subsequently mounted onto glass slides for fibres to be counted by phase contrast optical microscopy. Some exclusion of very coarse particles occurs owing to elutriation in the vertical cowl, but its selection characteristics (Walton, 1954) would have very little effect on the sample. Whether a fibre should be counted is decided at the analytical stage, based on its length, diameter and aspect ratio.

The counting of fibres can be hindered by the presence of other dust or coarser fibres on the filter. Recently, in the UK, the procedures for air testing in premises after asbestos removal work have specified that sampling must be preceded and accompanied by dust disturbance, normally brushing, that generates dust to at least the same extent as may be caused by subsequent normal activities (HSE, 2005). Conscientious application of this guideline increases the amount of particulate dust in the air, and the HSE recommends that sequential shorter period samples may be needed to obtain countable samples. An alternative, and perhaps more reliable and efficient solution, might be the use of a suitable size-selective sampler to obtain countable samples in such cases.

For measurements of concentrations of non-fibrous dust in workplaces, there are conventions for sampling the aerosol fractions that would penetrate certain regions of the respiratory tract: the respirable fraction for dust reaching the alveolar lung, the thoracic fraction for dust penetrating beyond the larynx and the inhalable fraction for dust entering the respiratory tract (beyond the nose and mouth). These sampling conventions have been agreed to internationally in the early 1990s (ACGIH, 1993; CEN, 1993; ISO 1993b). At about the same time, there was also recognition of the potential advantages of using size-selective sampling for fibres and that the thoracic samplers should, in theory, exclude almost none of the fibres that would normally be counted under the standard rules for counting fibres (Dement 1990; Lippmann, 1994 a,b). Indeed, a WHO working group (WHO, 1997, page 8) considered that, in the future, a thoracic sampler might be adopted instead of the cowed sampler as it would reduce large particle

background and it might remove the requirement to determine fibre diameter since all fibres penetrating beyond the larynx could be relevant to adverse health effects. Fibres reaching the bronchi may deposit directly near the sites where human lung cancers usually occur [near the bifurcations in bronchial airways, e.g. Carter *et al.* (1976) and Nagomoto *et al.* (1993)], and fibres that deposit in the terminal bronchioles or alveoli may be retained in the lung for a long time. An aerodynamically size-selected sample might also be useful if new fibres are developed and manufactured from materials with a very different density from that of asbestos for which the maximum diameter (of 3 μm) for countable fibres corresponds to the upper limit of the respirable size range. For example, the HSE's criteria document for an occupational exposure limit for para-aramid fibres noted that a para-aramid fibre with a diameter of 4 μm would have approximately the same gravitational settling speed and, therefore, approximately the same penetration into the lung as a mineral fibre with a diameter of 3 μm (Minty *et al.*, 1995). The HSE review also noted that a change in the diameter specification in the counting rules would be inconvenient for operators monitoring environments where mineral fibres might also occur. Their recommendation for para-aramid fibres suggests that different cut-off diameters may indeed be appropriate (perhaps needed) for other new fibres, but would be inconvenient to apply except by aerodynamic selection.

As the counting rules for fibres (e.g. HSE, 1995) include only fibres that have an aerodynamic diameter within the respirable range, it might be thought that a respirable sampler would be best. Indeed, the fibres that can be calculated to have an aerodynamic diameter within the respirable range are often called respirable fibres. However, the counting rules include every fibre within the specified size range [approximating to a sharp cut at ~ 7 μm aerodynamic diameter (d_{ae})], whereas the respirable sampler collects a fraction that progressively decreases with particle size (e.g. 50% at 5 μm d_{ae}). So a respirable sampler would exclude some of the fibres that would be collected and counted currently, as described in more detail by Baron (1996) who calculated that the thoracic selection convention should not have that problem.

A thoracic sampler is designed to have an aerodynamic selection characteristic such that selection should depend on the aerodynamic diameter (d_{ae}) of the particle or fibre. For a fibre, d_{ae} is a function of mainly the physical diameter and the fibre density, and has only a slight dependence on fibre length. However, the thoracic samplers were designed for, and tested with, isometric particles. In order to evaluate whether they may be used for the sampling of non-isometric particles such as fibres, it is important to examine whether their performance might also be dependent on fibre length, e.g. owing to interception

of long fibres on surfaces of the size-selective part of the samplers.

In the late 1990s, two separate but complementary projects were undertaken to examine the performance of thoracic samplers for fibres. In one, reported in this paper, the size-selection characteristics of several thoracic samplers were measured using a polydisperse fibrous aerosol containing fibres with aerodynamic diameters that spanned the thoracic size range. In the other project, Maynard (2002) optimized a procedure for classifying a fibrous aerosol by length and then used length classified aerosols to assess whether penetration through several thoracic samplers depended on the length of the fibres. There were several clear differences in these two approaches. Here, we collected the sampled fibres on filters and then counted and sized the fibres to enable aerodynamic diameters to be calculated for each fibre. Comparison of penetration and challenge samples produced the penetration characteristics, relative to aerodynamic diameter, to be compared directly with the thoracic convention. The other approach did not need the detailed size information on each fibre, just the relative numbers penetrating which were obtained by automated counting with an aerodynamic particle sizer (APS). The number of fibres penetrating some thoracic samplers was independent of fibre length (at least for fibre lengths up to 60 μm), hence implying that the samplers' penetration characteristics for a fibrous aerosol should be no different from that for an isometric aerosol.

The experimental difficulties and sources of uncertainty were markedly different in these two projects, so the combination of results from the two is much more powerful than the findings from one alone; the adoption of a major change in sampling practice would need to be strongly supported by evidence of the validity of the new method and its comparability with results from the old method.

In this study we also examined whether the thoracic samplers would produce adequately uniform distribution of fibres on the membrane filter's surface. In fibre counting, randomly selected fields are examined, and some variation in the number of fibres in each field is expected; however, systematic bias between areas of the filter could lead to greater dependence on field selection and hence greater variation. Therefore, an examination of the extent of variation in loading over the filter surface both for the thoracic samples and the standard cowled samples sought to assess the extent of any difference in variation.

APPROACH

In this project, four samplers for the thoracic fraction were investigated to assess how well they follow the thoracic convention when sampling fibres. A

routine sampler for fibrous dust (as commonly used in Europe) was also included in the tests, to provide a comparison. In this series of tests:

- The distribution of sample over the surface of the filters (in each of the samplers) was assessed initially using monodisperse, unit density, polystyrene latex particles. Non-uniformity of deposit might arise either if the flow through the filter was not uniformly distributed across its surface or if particles with high inertia were projected towards a part of the surface by the inlet geometry. Therefore, these tests were undertaken with two particle sizes, 1 and 10 μm , spanning the range relevant to thoracic samples.
- The sampling performance was assessed with an aerosol generated from a batch of fibres that had been specially prepared (by the manufacturer, Schuller's Mountain Technical Centre) to give a spread of aerodynamic diameters across the thoracic range.
 - Whole-filter samples were counted by optical microscopy, recording the number of fibres on each field, to assess the extent of any systematic departure from random variation.
 - Fibres on sets of samples were counted and sized by scanning electron microscopy (SEM). Then aerodynamic diameters (d_{ac}) were calculated for each fibre from its dimensions. The samplers' size-selection characteristics were obtained by taking the ratio of concentrations from the thoracic or cowled samplers to the average concentration from the two semi-isokinetic samplers, for fibres in the defined ranges of length and d_{ac} .

Aerosol generation and sampling, for isometric particles and fibres, was undertaken at the IOM. Samples with isometric particles were evaluated at the IOM. The fibre samples were evaluated, by optical or electron microscopes, at four of the collaborating laboratories (IOM, INRS, NIWL and BIA). The data were returned to IOM for analysis, and the findings were reviewed and agreed upon jointly.

THE SAMPLERS

There are only a few thoracic size-selective sampling instruments available. Four such sampling instruments were evaluated in this study, and one of them was developed, by modification of the SIMPEDS respirable sampler, as part of the overall programme of work relating to this study (Lidén and Gudmundsson in Jones *et al.*, 2001). The modifications involved changes to the length, inner diameter and outer diameter of the vortex finder and the sampling flow rate. Three of the instruments were

intended for use as personal samplers and one was designed for stand alone use with high flow sampling. The four thoracic samplers were:

- (i) GK2.69 Cyclone (Kenny and Gussmann, 1997; Maynard, 1999), a tangential flow cyclone designed to operate at 1.6 l min^{-1} for a thoracic selection where the sampled aerosol is normally collected onto a 37 mm diameter filter held in a standard 37 mm filter cassette placed on the cyclone outlet.
- (ii) Modified SIMPEDS cyclone, a form of the standard SIMPEDS cyclone that is modified to give a thoracic cut. Sampling is carried out at 0.8 l min^{-1} .
- (iii) IOM thoracic sampler (Aitken and Donaldson, 1995) designed to separate out the extrathoracic fraction using a foam pre-separator, allowing the thoracic fraction to be collected onto a 37 mm diameter filter. The sampler is operated at 2.0 l min^{-1} .
- (iv) CATHIA Sampler, a variant of the CIP-10 personal sampler designed for stand alone use (Fabriès *et al.*, 1998). The name is an acronym meaning, in French, thoracic, inhalable and respirable aerosol sampler. It is configurable with a range of inlets, although in this investigation the thoracic inlet was used. Sampling is carried out at 7 l min^{-1} onto a 37 mm diameter filter.

To provide a comparison, the study also evaluated the Cowled Sampling Head, which is the currently accepted method of sampling fibrous aerosols in a number of countries. In this sampler, the aerosol is sampled via a 25 mm diameter vertical elutriator onto a 25 mm diameter filter, at flow rates between 1 and 8 l min^{-1} (HSE, 1995). Although vertical elutriators can be designed to give specific size-selection characteristics [e.g. Walton (1954) described the design and theory of a vertical elutriator to give a respirable cut], the flow rate in this case was too high for significant selection except for particles larger than the thoracic size range.

In a calm air test chamber with a fibrous aerosol, the test samplers were compared with a pair of semi-isokinetic samples using a method similar to that described by Aitken *et al.* (1999). These semi-isokinetic samplers comprised probe samplers mounted on a horizontal arm rotating slowly (1 r.p.m.) such that the sampler's forward speed matched the inward velocity of the sampling flow, thus producing approximately isokinetic sampling. These two probe samplers were mounted on diametrically opposite ends of the rotating arm.

Prior to the tests described in this paper, the performance of the thoracic samplers was evaluated with isometric particles, using spherical particles and an automated particle counter, the APS. The use of an

automated counter enabled high numbers of particles to be counted, and thus allowed the sampling characteristics to be measured with high precision. These tests are fully described elsewhere (Maynard, 1999; Jones *et al.*, 2001), and essentially they showed that these thoracic samplers had selection characteristics that while not identical to convention were more than close enough. In fact, the main departure was some oversampling (relative to convention) of particles with aerodynamic diameter $<5 \mu\text{m}$. However, this would not be a disadvantage for comparability with the cowled sampler in the measurement of respirable fibres.

METHODS

The polystyrene latex particles were purchased as aqueous suspensions (of 1 or $10 \mu\text{m}$ particles). The suspension was diluted in alcohol and dispersed by an air-jet atomizer into a conditioning tube that was $\sim 1 \text{ m}$ long and led into the top of a conical inlet to a 1 m^3 cubical test chamber. Supplementary clean filtered air was injected along with the particles, so that the particles were dry before reaching the test chamber. A Royco optical particle counter was used to check the distribution of aerosol in the chamber by sampling at multiple points and to ensure (by counting the number of particles in suitable size bands) that the particles were well separated.

The fibre sample obtained for the study contained plenty of fibres with aerodynamic diameter $\sim 10 \mu\text{m}$. Summary indicators of the fibres' physical dimensions include:

- geometric mean diameter of $2.7 \mu\text{m}$ [geometric standard deviation (GSD) 2.1] and geometric mean length of $34.0 \mu\text{m}$ (GSD 2.2);
- median diameter and median length of 3.1 and $33.4 \mu\text{m}$, respectively;
- 72% of fibres had diameter $>2.0 \mu\text{m}$ and 75% had length $>20 \mu\text{m}$.

The bulk fibre sample poured like a powder and was suitable for feeding from a grooved rotating table dispenser with a compressed air atomizer. This system produced mainly separate single fibres and suitable airborne fibre concentrations.

During the sampling experiments with fibres, the test samplers were mounted on a platform that oscillated very slowly, more slowly than the movement of the rotating probes samplers, to minimize the effects of any spatial non-uniformity of the aerosol in the chamber.

The flow rates and filter areas were markedly different between these samplers (as summarized in Table 1), so the sampling duration for each sampler had to be controlled to produce loadings in the countable range for all samplers. For the tests, the samplers requiring shorter sampling times for equal loading

Table 1. Sampling flow, filter area and sampling times for equal loading, with the thoracic samplers compared to the cowled sampler operating at 2 l min^{-1}

Sampler	Filter diameter (mm)	Flow (l min^{-1})	Flow/area ($\text{ml min}^{-1} \text{mm}^2$)	Exposure times giving equal loading (min)
CATHIA	37	7	7.3	6.0
GK2.69	37	1.6	1.7	25.8
Modified SIMPEDS	25	0.8	1.7	24.9
IOM thoracic	37	2	2.1	20.6
circling probe	37	1	1.1	41.2
Standard cowled sampler	25	2	4.3	10.0

The flow through the cowled sampler can be varied, but the thoracic samplers require the specified flows to produce the intended selection characteristics.

were switched on and off for alternate periods so that their cumulative sampling time was less but spread throughout the overall sampling period. Sampling by intervals collected a representative sample of aerosol within the time when the other samplers were running. This enabled samples with suitable density for counting to be obtained from all samplers.

For the isometric particle tests, 24 filter samples (four sets of 6 samples) were collected for each particle size, i.e. a total of 48 samples.

The numbers of filter samples collected for the fibrous aerosols were:

- 24 samples for optical analysis, comprising four for each sampler (including the total aerosol sampler), and thus four sets of 6 samples (1 sample per sampler);
- 77 samples for SEM analysis, comprising 11 for each sampler (including the total aerosol samplers), and thus 11 sets of 7 samples (2 samples from the rotating probe sampler, one from each of the other samplers).

The samples with isometric particles were evaluated by optical microscopy, using a rectangular grid pattern to define the positions of counting fields. Field locations were determined by locating the central line of the grid markings on the filter, and then traversing the microscope stage by $\sim 3.5 \text{ mm}$ (for 25 mm diameter filters) or by 5 mm (for 37 mm diameter filters). A series of parallel traverses produced a total of 37 fields for each filter. The magnification was chosen to suit the size of particles being counted: $\times 500$ for the $1 \mu\text{m}$ particles and $\times 125$ for the $10 \mu\text{m}$ particles.

The samples with fibres for optical microscopy were evaluated by scanning in a defined pattern, along parallel chords, $\sim 1.5 \text{ mm}$ apart on 25 mm diameter filters and 2 mm apart on 37 mm diameter filters, to give a total of 200 fields counted per filter.

The fibre samples for SEM evaluation were mounted by each of the four laboratories using their usual techniques, and then evaluated using agreed procedures for the counting and sizing. Each lab received three sets of samples (except for

one lab which received two sets of samples) for SEM evaluation.

The experimental details are fully described in Jones *et al.* (2001).

CALCULATIONS RELATING TO AERODYNAMIC DIAMETER OF FIBRES

For each fibre counted and sized by SEM, its aerodynamic diameter was calculated from the relationship below. The aerodynamic diameter of each fibre was calculated from the equation of Cox (1970):

$$d_{\text{ae(perp)}} = d \sqrt{\frac{9\rho}{8} (\ln_e(2\beta) + 0.193)} \quad (1)$$

where $d_{\text{ae(perp)}}$ is the aerodynamic diameter for a fibre moving perpendicular to its axis, ρ is the density of the fibre and β is the aspect ratio (length/diameter) of the fibre. We used the aerodynamic diameter for motion perpendicular (rather than parallel) to its axis because the fibres would tend to align with the flow, and the sedimentation or inertial deposition would be dependent mainly on motion perpendicular to the axis of the fibre rather than parallel to it. Griffiths and Vaughan (1996) showed that the sedimentation of fibres under gravity was best described by assuming motion perpendicular to the fibre's axis and that the aerodynamic diameter could be calculated using equation (1). The comparison with an aerodynamic diameter for sedimentation perpendicular to the fibre axis is therefore a good choice for comparing the samplers' size selection with the thoracic selection curve.

The data were then used to estimate the number of fibres in intervals of $d_{\text{ae(perp)}}$ and subdivided into classes of fibre length. The number of fibres (in each class) on the thoracic filter sampler was then compared with the average concentration of such fibres as measured from the two circling probe samplers. From each set of 7 samples, an estimate of size-selection efficiency was obtained for every size class for each sampler. From the first four sets of 7 samples,

we obtained a set of data from each lab, and hence the (geometric) mean values over the four labs. From the next four sets, and the next three sets, two more mean results were obtained. Then the overall geometric mean and GSD were calculated from these three intermediate mean results. This GSD serves to calculate the error bar in the plots of overall mean selection characteristics; each error bar extends from the geometric mean divided by GSD to the geometric mean multiplied by GSD. (If expressed on the log scale, this would be the mean \pm 1 SD.) Thus, the error bar reflects the amount of variation between these three mean values (over laboratories on independent sets of samples).

RESULTS

Distribution of sample over the filter surface

The tests with the isometric particles produced comparisons of the distributions across the filter surface of the samples taken with the thoracic samplers, the cowled sampler and the probe sampler. Plots (of mean values across four tests) are shown in Fig. 1a and b. These plots showed that for most of the thoracic samplers and for the cowled sampler, the distributions of particles were very similar in the degree of variation across the surface; all had reasonably good uniformity for the 1 μ m particles. However, for the coarse (10 μ m) particles, there was evidence of a localized high concentration adjacent to the port from the cyclone separator of the Modified SIMPEDS sampler. There was also some indication of hotspots or asymmetry of distribution on the GK2.69 and the rotating probe, but not as marked as the hotspot on the Modified SIMPEDS.

The variation from field to field is summarized in Table 2, which lists the ratio of the variance to the arithmetic mean count of particles per field. Each value is a geometric mean of the results from four filters. For a purely random distribution, described by the Poisson distribution, the variance equals the mean. Most values for the particles are \sim 1.2 or 1.3; the value of 2.2 for the Modified SIMPEDS sampler tested with 10 μ m particles is noticeably larger, reflecting the effect of the localized high concentration. The rotating probe samplers produced higher loading on one half of the filter for the 10 μ m particles, and this is reflected in the ratio in Table 2.

The results obtained from counts of fibres per field over a defined grid pattern are summarized in the final column of Table 2. For the fibres counts, the mean ratios are close to 1 except for the Modified SIMPEDS sampler. Figure 2 shows the distribution of fibre counts (accumulated over all counts for each sampler) over the filter surface. The standard cowled sampler shows just as much random variation as any of the thoracic samplers, except the Modified SIMPEDS. The distribution

of fibres on the filter surface was therefore considered to be satisfactory for collecting samples for fibre counting for most of the samplers. The greater systematic bias seen on the Modified SIMPEDS was a disadvantage for fibre counting, but not a sufficient reason to exclude the sampler from the further tests of performance with fibres.

Size-selective sampling for fibres

The size-selection characteristics of the samplers, derived from the SEM fibre count data, are plotted in Figure 3. The data are for fibres subdivided into those shorter than 15 μ m, those between 15 and 30 μ m, and two classes for fibres longer than (30 or 50 μ m); the longer than 30 μ m class includes fibres longer than 50 μ m. More variability was expected in the data for the latter, since there were fewer fibres in this length class, but it was included to increase the possibility of detecting any dependence on fibre length.

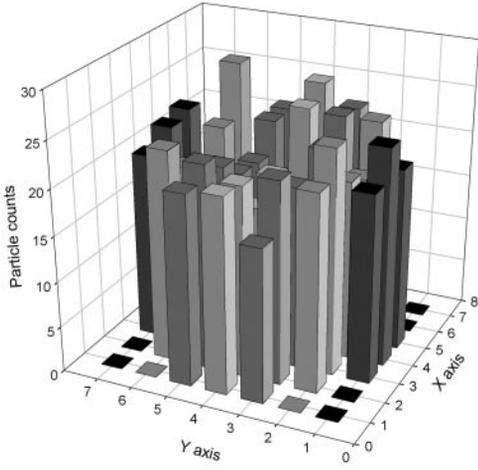
The first graph shows the performance of the cowled sampler, and the thoracic convention is included in this graph only for consistency with the other plots; the cowled sampler is not designed to produce the thoracic size selection. The error bars indicate that there is considerable uncertainty in each individual size interval, but the overall trends appear very consistent. For the cowled sampler, several error bars are shown; whereas for the other samplers, error bars are shown for just one of the length classes. The multiple error bars give a general impression of the amount of variation; the single bars show it more clearly for representative length classes.

The graphs for three of the thoracic samplers (GK2.69, CATHIA and Modified SIMPEDS) show no sign of dependence on fibre length. For example, the data for the longer fibres ($l > 30$ μ m or $l > 50$ μ m, the triangle symbols) are neither generally lower than those for either of the two shorter fibre length classes, nor do they show a different trend relative to d_{ae} . For the IOM thoracic sampler, the sampling efficiencies are slightly higher for the shortest length class than for the other length classes.

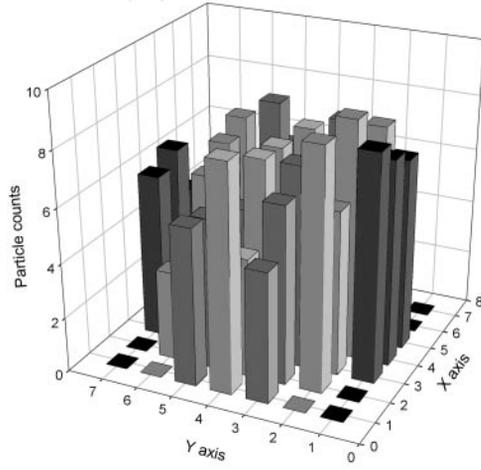
For the thoracic samplers, the data for all four fibre length classes lie fairly close to the curve for the thoracic convention. For fibres with $d_{ae} < 5$ μ m, the estimates of E are slightly higher than the convention, except for the IOM foam sampler which produced values \sim 0.8. For values of $d_{ae} > 10$ μ m, the trend is very consistent with the thoracic convention. Thus, the exclusion of coarse fibres (and particles) that would interfere with a count is achieved by these four samplers.

The one apparent anomaly in the results in this graph is that the values for the sampling efficiency for the cowled sampler appear to be nearer to 1.1 or 1.2 than 1. Some values greater than 1 might arise from the random variation, and the error bars span the unity.

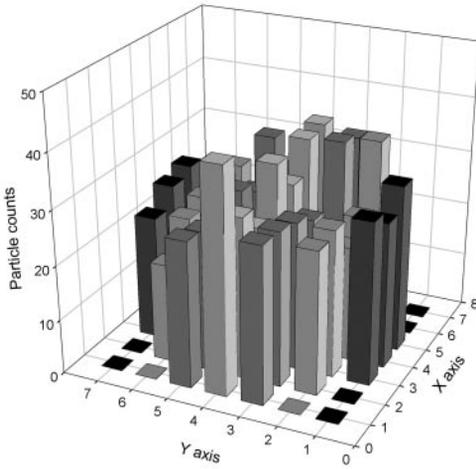
(a) CATHIA, 1 μm particles



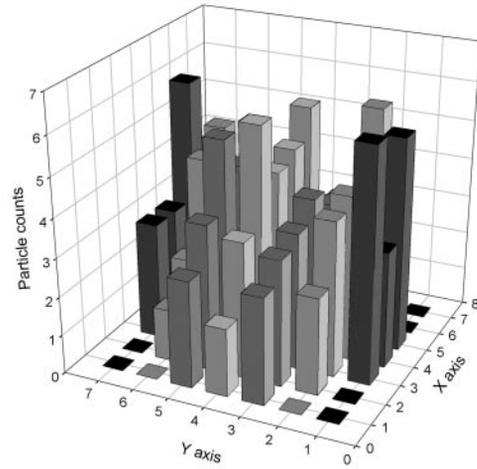
CATHIA, 10 μm particles



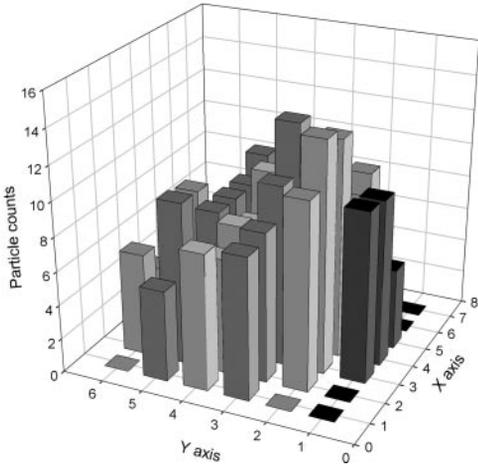
IOM foam thoracic, 1 μm particles



IOM foam thoracic, 10 μm particles



Cowled sampler, 1 μm particles



Cowled sampler, 10 μm particles

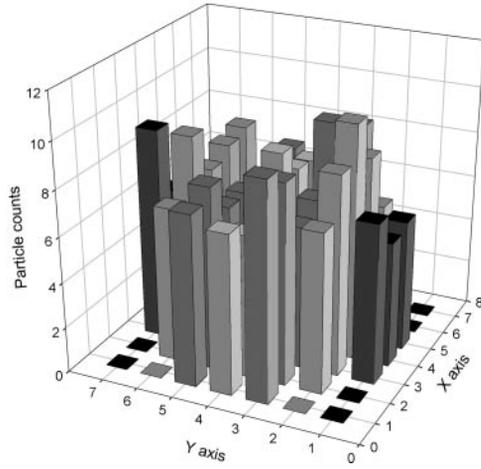


Fig. 1. Continued.

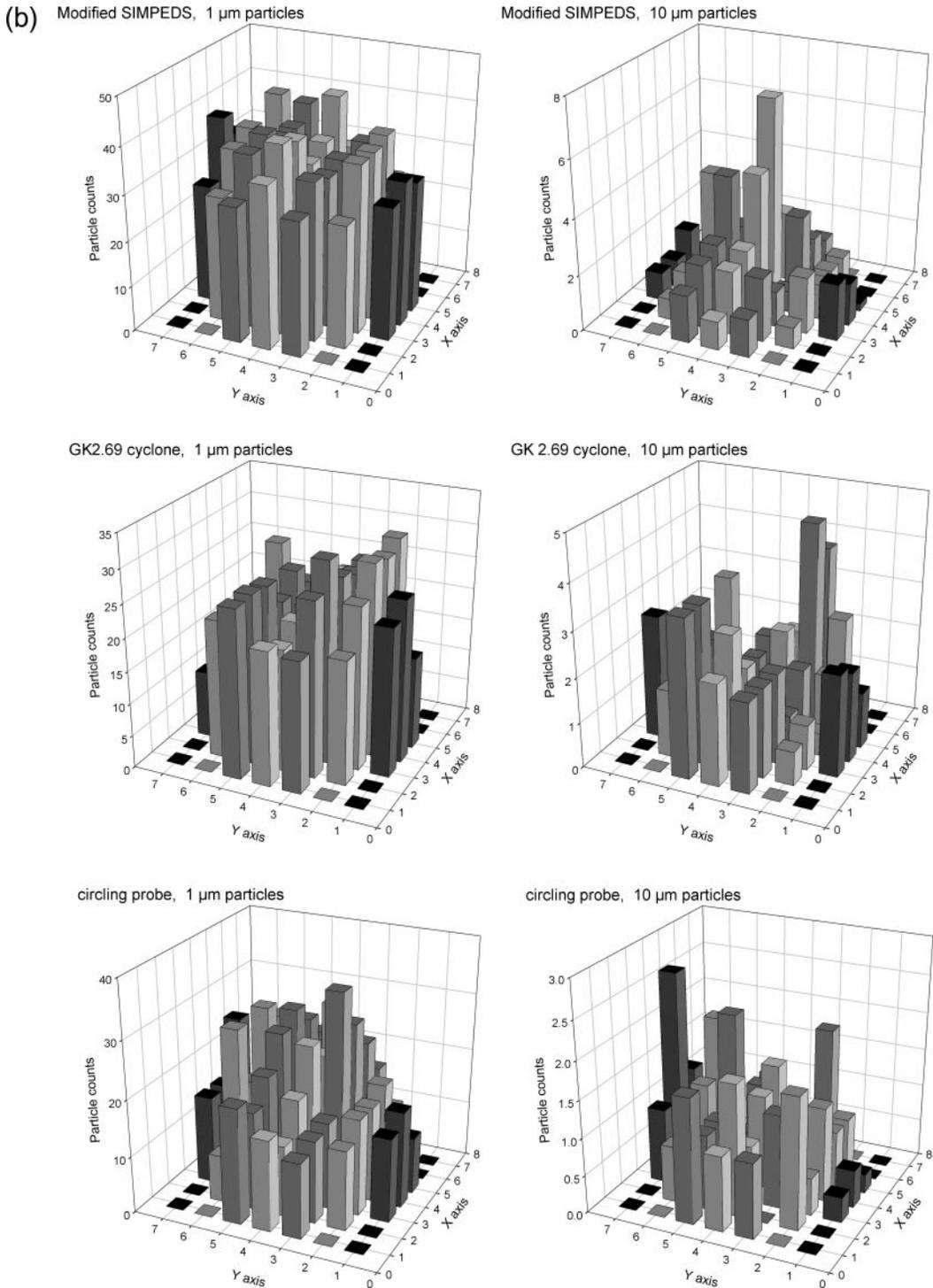


Fig. 1. The distributions of two sizes of spherical particles, 1 and 10 μm , over the surface of the sample filters: (a) for two thoracic samplers and the standard cowled sampler, and (b) for three more samplers (the cyclone thoracic samplers and the circling probe samplers). Means from four tests.

DISCUSSION AND CONCLUSIONS

Size-selective sampling

The logical case for using size-selective samplers for sampling fibres has been put forward by others

nearly a decade ago, as described in the Introduction. However, acceptance of an alternative to the current standard methodology for sampling fibres (the cowled sampler) is unlikely to happen without strong evidence to support the validity of size-selective

Table 2. Relative uniformity of distribution of isometric particles or fibres over the filter surface for the test samplers and the standard cowled sampler

Sampler	Variance/ mean count (geometric mean ratio)		
	1 μm particle tests	10 μm particle tests	Fibres on samples counted by optical microscopy
CATHIA	1.3	1.2	0.904
IOM Thoracic	1.3	1.3	0.956
Modified SIMPEDS	1.2	2.2	1.20
GK2.69	1.4	1.2	1.00
Rotating probe	1.5	4.6	0.97
Standard cowled sampler	1.3	1.1	0.89

Values are based on four filters per sampler, for each test.

samplers. The results of this study are intended to contribute to the assessment of the suitability of thoracic samplers for fibres.

The types of the size-selection method differed quite substantially between the four thoracic samplers tested, so that the test results should be a good indicator of how suitable size-selective samplers are in general, and whether certain types of size selection are likely to be advantageous for fibres. The potential for fibre length to cause interception of fibres might be thought likely to differ between a cyclone and a foam selector, or the inertial impaction design of the CATHIA. The contrast in design of size-selection mechanisms increases the general relevance of the results of the study.

Distribution of the deposit on the filter surface

The distribution of fibres over the filter surface is important for samples that are to be assessed by optical microscopy. Under normal counting rules, only $\sim 1\%$ of the surface of a (25 mm diameter) filter is examined by counting 100 fields. (If the entire surface were examined, then an uneven distribution would not affect the total count.) However, for a count based on random fields spread over the surface, a bias in the distribution of fibres is likely to lead to a greater variation in the fibre counts. The evaluation of distribution for isometric particles, of two sizes, and for fibres, examined the extent of non-uniformity of distribution thoroughly. The results indicated some high spots of deposition for the Modified SIMPEDS cyclone sampler; these hotspots were evident for the 10 μm particles but not the 1 μm particles, indicating that it was an inertial effect due to the flow pattern at the port from the cyclone pre-separator.

Blackford *et al.* (1985) examined the distribution of particles over the surface of a SIMPEDS operating as a respirable dust sampler. They found a non-uniform

distribution of dust over the filter surface, with the coarser particles being deposited by inertial effects in a spot aligned with the flow from the entry port. The particle-size dependent variation in the pattern of deposition on the filter surface of a SIMPEDS is thus a common finding from the present and previous studies.

For the other three thoracic samplers, distribution over the filter surface appeared to be as good as that for the current standard sampler, the cowled sampler.

Aerodynamic size selection

The size-selection data obtained from the laboratory tests with fibres showed that the performance differed very little from that expected for isometric particles. At $d_{ac} < 7 \mu\text{m}$, three samplers (most clearly the Modified SIMPEDS and the CATHIA, and to a lesser extent the GK2.69) produced a sampling efficiency slightly higher than the thoracic convention which would tend to be helpful for consistency with the cowled sampler in measuring concentrations of respirable fibres. For the IOM foam thoracic sampler, the selection (E) was slightly below the convention for $d_{ac} < 10 \mu\text{m}$, and more consistently so for fibres longer than 15 μm . Interestingly, this is the one thoracic sampler for which Maynard (2002) did find a length-dependent trend with sampling efficiency reducing with length $>30 \mu\text{m}$.

For GK2.69, Modified SIMPEDS and CATHIA, the different length classes showed remarkably similar trends with respect to d_{ac} . In particular the selection (E) of fibres longer than 30 or 50 μm did not appear to be any lower than that for fibres in the 15–30 μm or $<15 \mu\text{m}$ classes. This is consistent with the findings of Maynard (2002) who found an absence of length-dependent sampling effects for these three samplers. Maynard also examined the selection of fibres in a modified IOM inhalable sampler equipped with a foam size selector and found the selection to be independent of fibre length. This provided an interesting contrast with the results for the foam selector in the IOM thoracic sampler. Maynard noted that the residence time of the fibres in the foam selector was much less in the modified IOM inhalable sampler than in the IOM thoracic sampler. Maynard suggested that residence time would be important if length-dependent phoretic deposition mechanisms, such as dielectrophoresis, played a role. Increased deposition due to interception was considered unlikely, as the mean pore size of these foams was an order of magnitude larger than the longest of the fibres used in Maynard's experiments.

The performance of size-selective samplers for fibres has also been examined by Iles (1990) who used an APS to measure the aerosol penetrating the cyclone of the SIMPEDS, and thereby demonstrated that the cyclone produced a respirable selection [as

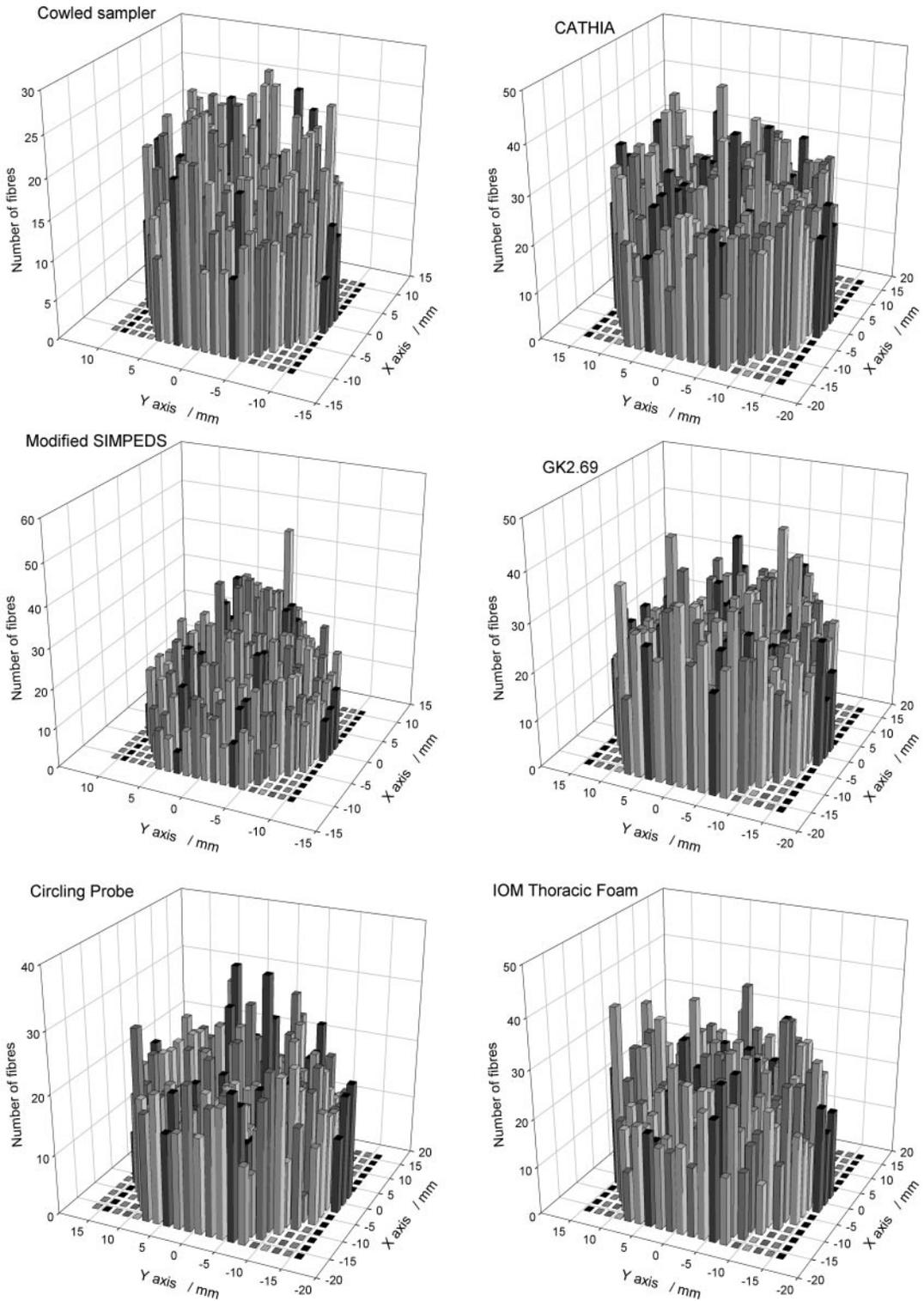


Fig. 2. Distribution of fibres over the surface of the filter samples. The data are the total fibre counts from counts over a regular grid pattern, from 12 filters per sampler.

defined by the BMRC curve (Orenstein, 1959)] for an aerosol of glass fibres. Iles noted that a limitation of his study was that the APS, which is calibrated on spherical particles, was assumed to give a direct

estimate of the aerodynamic diameter of the fibres. Nevertheless, his results contribute to a body of evidence that indicates that aerodynamic size selectors do operate correctly for fibres.

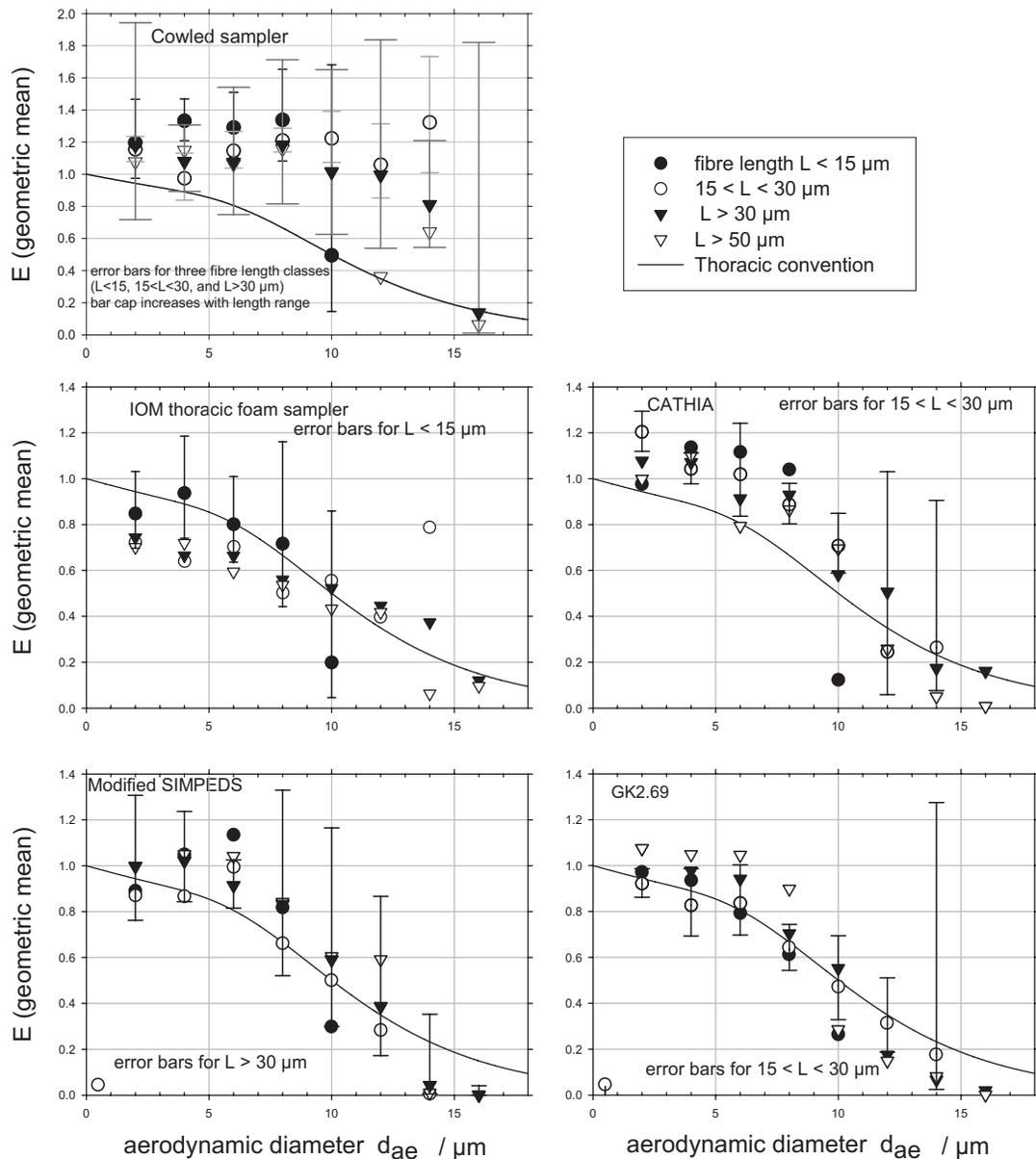


Fig. 3. Aerodynamic size-selection (E) of fibres compared with aerodynamic diameter (d_{ae}) calculated from fibre dimensions, for fibres subdivided into length classes, for each of the samplers. Note that the length classes for fibres longer than 30 or 50 μm overlap. Error bars are defined in the text (in the section 'Calculations').

Flow rates and sample loading

These thoracic samplers produce their specified selection characteristics at a particular flow rate, which is a restriction that does not apply to the cowled sampler. For clearance sampling, sample volumes of at least 480 l are sought for a 25 mm diameter filter sample as it enables concentrations to be assessed down to the clearance indicator of 0.01 fibres ml^{-1} . For larger filters, the volumes would have to be proportionately higher (as indicated in Table 1) to achieve the same loading and hence the same sensitivity. Only the Modified SIMPEDS currently

uses a 25 mm diameter filter; however, it operates at half the flow rate of the GK2.69, so those two samplers produce the same filter loading for a given sampling time. The CATHIA sampler is a high volume sampler, but uses a 37 mm diameter filter and so operates at the same flow per unit area of filter as a cowled sampler at 3 l min^{-1} .

Conclusions and recommendation

The main conclusion is that thoracic samplers are suitable for sampling fibres. It is expected that such samplers may well be needed in situations where the

presence of coarse dust interferes with or prevents the reliable counting of fibres. The presence of coarse dust may be a greater issue now that air sampling after asbestos removal work has to be accompanied by vigorous dust disturbance to simulate subsequent work activities such as sweeping.

Further developments in the design of size-selective samplers may be desirable to achieve higher flow per unit area of filter, but the principle of the effectiveness of thoracic samplers for sampling fibres has been demonstrated in laboratory tests with fibres having a size distribution that spanned the aerodynamic size range relevant to the thoracic convention.

Acknowledgements—This study was supported by the Standards, Measurements and Testing programme of the European Commission (contract no. SMT4-CT96-2095) and also, for the IOM, by the UK Health and Safety Executive (contract no. 3545/R541.123). We also wish to thank our colleagues (Geoff Beaumont, Mrs Ildiko Laszlo) who made major contributions to the work in the laboratory.

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