Removal efficiency of high efficiency air filters against microbe-carrying particles (MCPs) in cleanrooms

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Abstract

The removal efficiency of high efficiency air filters was determined against microbe-carrying particles (MCPs) in the air supply to cleanrooms. Knowing the size distribution of MCPs in the air to be filtered, and the filter's removal efficiency against individual particle diameters, the overall removal efficiency was ascertained. The removal efficiency of individual species of microbes with a known size was also obtained. A variety of filters were investigated, and it was found that a filter 90% efficient against the most penetrating particle size (as classified by EN 1822) was greater than 99.99% efficient in removing MCPs. The effect of filter efficiency on the microbial concentration in both the air supply and the cleanroom air was studied, and no practical improvement in the air quality was obtained by filters that had a removal efficiency greater than 99.99% against MCPs. Use of a filter suitable for removing MCPs, rather than sub-micrometre particles, would give a reduction of about 6 to 8-fold in the pressure differential across the filter, and a substantial reduction in the energy costs of running a cleanroom.

Key words: removal efficiency, microbes, micro-organisms, high efficiency air filters, HEPA, cleanrooms, energy efficiency, fan power.

1. Introduction

The airborne cleanliness of a cleanroom is dependent on large quantities of highly-filtered air being used to dilute and remove contamination from the room. High efficiency air filters are classified by EN 1822-1:2009 as Efficient Particulate Air (EPA) filters, which remove between 85% and 99.5% of the MPPS (most penetrating particle size) particles, i.e. the particle size that most easily penetrates the filter, High Efficiency Particulate Air (HEPA) filters, which remove between 99.95% and 99.995% of MPPS particles, and Ultra Low Penetration Air (ULPA) filters, which have a removal efficiency equal to, or greater than, 99.9995% of MPPS particles.

Cleanrooms are very expensive to run, and one manufacturing company has reported (Matsuki and Tanaka, 1998) that the energy consumption of their semiconductor plants exceeded 100 million kWh per year. Schicht (1999) reported that 65% to 75% of the cost of running a cleanroom is energy. Typical running costs for providing conditioned air are about 65% of the total energy (Tschudi et al, 2001). Much of this energy is used by fans to overcome the pressure drop across the high efficiency air supply filters, which is in the region of about 150 Pa when new, and about 400 Pa when used. This filter pressure can be as great as the entire pressure drop in a simple air conditioning and air distribution system used in offices, libraries, and similar areas. If the performance of filters exceeds what is necessary, large amounts of energy are wasted.

Cleanrooms are used by a wide variety of industries to minimise contamination of the product from airborne particles. In pharmaceutical, medical device, food, and similar manufacturing areas, the most important contaminants are microbes, but their cleanrooms are similar in design to those in industries where inert sub-micrometre particles are important, and the same high efficiency of air filters is used.

Most of the cleanroom air is recirculated back to the air conditioning plant where it is mixed with fresh air, conditioned, filtered, and supplied back to a cleanroom. The supply air to be filtered is therefore very similar to that found in the cleanroom. Although microbes in their unicellular form are no more than a few micrometres in size and may be less than 1 µm e.g. *Staphylococcus aureus* is about 0.9 µm (Kowalski et al, 1999), they are seldom found in a unicellular form in the air of occupied rooms, but carried on skin cells (Davies and Noble, 1962). The sole source of MCPs in cleanrooms is normally personnel. People shed approximately 10^9 skin cells per day, the skin cells being about 33 µm x 44 µm in surface area, and between 3 µm and 5 µm thick (McIntosh et al, 1978). Some of these skin cells carry skin microbes and are known as microbe-carrying particles (MCPs) with an average equivalent diameter of about 12 µm (Noble et al, 1963; Whyte and Hejab, 2007). When people wear ordinary indoor clothing, the airborne dispersion rate averages about 2400 MCPs per minute, although this can be reduced by about 10 to 100 times by cleanroom clothing, which acts as a body filter (Whyte and Bailey, 1985 and Whyte and Hejab, 2007).

Investigations into the removal of MCPs by air filters have been rarely reported. A study was made of air supply filters in a hospital ward (Whyte, 1968), which had filters with a relatively low efficiency that ranged from about 90 to 99.9% when tested against an aerosol of about 5 µm diameter. The removal efficiency of MCPs was found to be similar to the removal efficiency against the 5 µm test aerosol. However, it has not been possible to parallel these investigations and test high efficiency filters *in situ* because of the insensitivity of microbial air samplers, which will not normally measure concentrations less than 1/m³, and are therefore incapable of measuring the low concentrations of MCPs that pass through HEPA filters. However, a method has been devised and reported in this paper that uses the size distribution of MCPs to be filtered, and the filter's efficiency against individual particle diameters, to obtain an overall efficiency. In addition, a method for calculating the removal efficiency of a single species of microbes, with a known size, has also been reported.

2. Particle removal mechanisms

HEPA and ULPA filters use fibrous media to remove particles. The media is usually made from glass fibres that range in diameter from about 0.1 µm to 10 µm, with spaces between fibres much larger than the particles captured. An ULPA filter has finer fibres than a HEPA filter. The fibres criss-cross randomly throughout the depth of the filter media and do not give a controlled pore size. As airborne particles pass through the filter paper, they are captured and retained by the fibres. The three main removal mechanisms in high efficiency filters are Brownian motion, interception, and impaction. *Brownian motion* captures very small particles as they move in a random motion caused by constant bombardment with other small particles and air molecules. The increased length and changes in direction of the resultant random paths increases the likelihood that the particles will bump into the filter fibres, where they are retained. *Interception* occurs when airborne particles come close enough to a fibre to be attracted and retained. *Impaction* occurs when particles, with sufficient mass and momentum, leave the airstream passing round a fibre and strike the fibre. The largest particles are removed by impaction, medium sizes by interception, and the smallest by Brownian motion. The combined action of these forces gives a particle size that is the Most Penetrating Particle Size (MPPS), which is about 0.2 µm to 0.3 µm.

3. Calculation of filter removal efficiency

Theoretical models have been developed to calculate the removal efficiency of particles of known diameter by fibrous filters e.g. Davies (1973), Brown (1993), Dhaniyala and Liu (1999B), and Hinds (1999). Firstly, the removal efficiency of a single diameter of fibre, which has an efficiency equivalent to the whole filter, is calculated for each of the three main removal mechanisms, namely interception, impaction and Brownian motion. The total single-fibre removal efficiency against particles of a given diameter is then obtained by combining the effect of all the individual mechanisms. Knowing the total single fibre efficiency, and the characteristics of the filter media, the filter efficiency of the whole filter against a single particle diameter can be calculated. The filter efficiency model used in this article is that described by Whyte et al (2012), and based on the model outlined by Hinds (1999), with a correction suggested by Dhaniyala and Liu (1999B) for accurately calculating the equivalent fibre diameter of the filter.

4. Properties of the air filters studied and validation of the filter efficiency model

The properties of filter media used in high efficiency filters are difficult to obtain, being proprietary information held by manufacturers. However, Dhaniyala and Liu (1999A) reported the properties of various filter media they studied, and these are reported by Whyte et al (2012). The filters had particle removal efficiencies that ranged from 12% against 0.3 µm particles to 99.99995% against 0.12 µm particles, and included HEPA and ULPA filters commonly used in cleanrooms, as well as filters of lower efficiencies that might be suitable for the efficient removal of MCPs. The experimental removal efficiencies measured against 0.12 µm and 0.3 µm particles, as obtained by Dhaniyala and Liu (1999A), are given in Table 1. Also given in Table 1 are the removal efficiencies of the various filter media calculated by means of the theoretical model referred to in the previous section.

Table 1 shows that the efficiencies calculated by the theoretical model are close to those measured. Having demonstrated that the removal efficiency of filters against given diameters of particles can be calculated theoretically, the removal efficiency of filters against a known size distribution of MCPs, or sizes of individual species of microbes, is now calculated.

5. Filter removal efficiencies against MCPs

5.1 Size distribution of microbe-carrying particles

MCPs have a variety of shapes and densities that influence their movement in air. It is therefore conventional and convenient to consider the size of airborne particles in terms of equivalent particle diameter. The term 'equivalent particle diameter' is used differently in a variety of situations, but in this article it is defined as the diameter of a sphere of unit density (1g/cm^3) that has the same aerodynamic properties as the particle being considered.

It was established many decades ago that microbes in the air of occupied rooms are carried on skin cells dispersed by people (Davies and Noble, 1962). The size distribution of airborne MCPs has been studied in hospital rooms (Noble et al, 1963), hospital air conditioning plants (Whyte, 1968), and from personnel wearing cleanroom clothing (Whyte, 1986; Whyte and Hejab, 2007). These results are very similar and, by compiling them, the size distribution of MCPs in the air of occupied rooms is given in Table 2.

It may be seen from Table 2 that the size distribution of MCPs has an average equivalent particle diameter of 12 µm. Microbes are unlikely to have a unicellular size much less than 1 µm (Kowalski et al, 1999), and at that diameter they have a frequency of occurrence of about 1%. The size distribution given in Table 2 conforms well to a log-normal distribution, with a median diameter of

Table 1: Comparison of particle removal efficiency obtained by measurement and calculation

Filter code number	Removal efficiency by measurement		Removal efficiency by calculation	
	0.12 µm	0.3 µm	0.12 µm	0.3 µm
HF 0493	23%	8.9%	21%	12%
HF 0533	63%	55%	49%	35%
HD 2063	96%	96%	93%	90%
HB 5433	99.95%	99.98	99.60%	99.68%
HA 8183	99.9995%	NR	99.9987%	NR
HA 8193	99.99998%	NR	99.9999%	NR

NR= Experimental results not reported by Dhaniyala and Liu (1999A).

Table 2: Occurrence of MCPs equal to, and greater than, given equivalent diameters

Equivalent particle diameter (µm)	≤ 1	≤ 5	≤ 12	≤ 20	≤ 50
Cumulative occurrence	1%	25%	50%	75%	95%

12 µm and a geometric standard deviation of 2.7.

5.2 Calculation of removal efficiency of MCPs by high efficiency filters

As discussed in the previous paragraph, the size distribution of airborne MCPs in occupied rooms conforms well to a log-normal distribution. The probability density function (pdf) of a log-normal distribution can be calculated by the equation given by Whyte et al (2012) and is the larger of the two curves given in Figure 1. This curve is known as the 'unmodified pdf' curve. An upper limit of 50 µm was chosen as it accounts for about 95% of MCPs, and any larger sizes will not penetrate filters. A lower limit of 0.02 µm was chosen to include most MCPs and, owing to Brownian diffusion, all smaller MCPs will be removed.

If the frequency of occurrence of the various diameters found in the size distribution of MCPs is multiplied by the filter removal efficiency at the same diameter, the result can be plotted as a 'modified pdf curve', and shown as the smaller curve in Figure 1. The area under the unmodified curve represents all of the MCPs in unfiltered air, and the area under the modified pdf curve represents the MCPs that penetrate through the filter. Therefore, if the area under the modified curve is calculated as the proportion of the area under the unmodified pdf curve, the penetration of MCPs is obtained. The removal efficiency of the filter can then be calculated. Given in Table 3 is the particle removal efficiency of the filters against the MPPS, and the overall removal efficiency against the size distribution of MCPs.

Shown in Figure 2 is the particle removal efficiency of one of the filter media (HD 2063). The MPPS of the medium was 0.22 µm, with a removal efficiency at that size of 87%. More than 99.99% of the size distribution of MCPs will be removed by that filter.

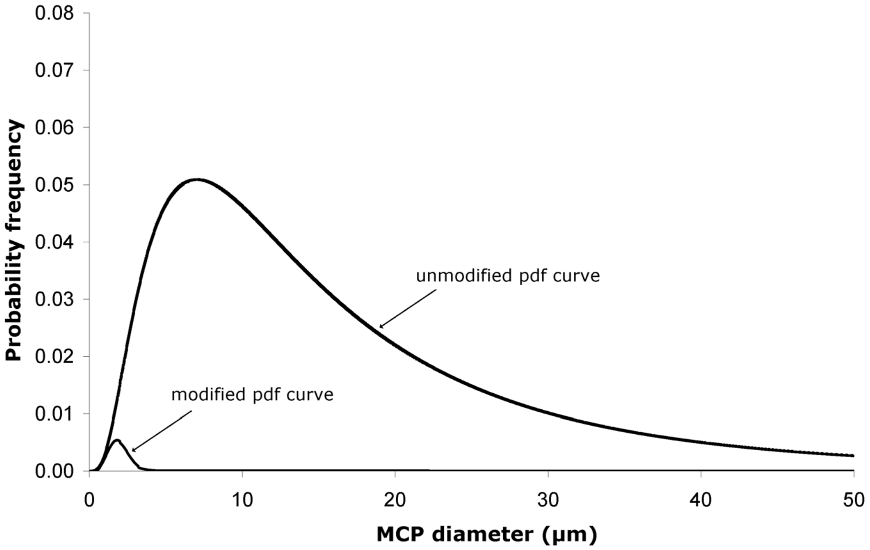

Figure 1: Unmodified and modified pdf curves

Table 3: MPPS and removal efficiency of MCPs of various filters

Filter code number	Particle removal efficiency at the MPPS	Removal efficiency of size distribution of MCPs
HF 0493	11% at 0.42µm	96.70%
HF 0533	35% at 0.3 µm	99.64%
HD 2063	87% at 0.22 µm	99.9946%
HB 5433	99.15% at 0.2 µm	99.999903%
HA 8183	99.987% at 0.22 µm	99.9999982%
HA 8193	99.9988% at 0.22 µm	99.99999989%

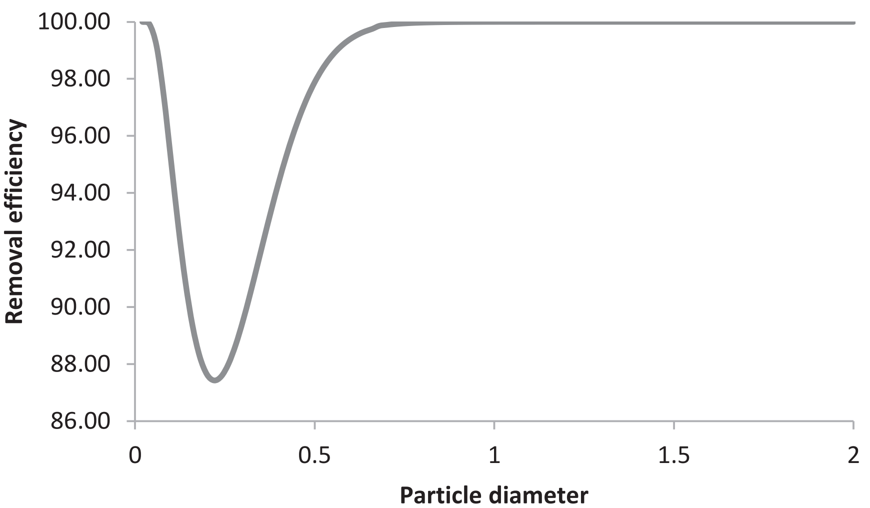

Figure 2: Particle removal efficiency of HD 2063 filter medium

6. Removal efficiencies of individual species of microbes

The method described in the previous section 5.2 can be used to calculate a filter's removal efficiency against the distribution of sizes of MCPs in the air recirculated from cleanrooms. However, the removal efficiency can also be calculated for a known size of microbe by using the filter efficiency model described in section 4. Using the filter efficiency model, the minimum sizes of microbes that will be removed at an efficiency of either 99.9% or 99.99% was calculated for the range of filters investigated, and is given in Table 4. It can be seen in Table 4 that a filter that is 87% efficient at the MPPS will remove 99.9% of microbes down to 0.9µm, and 99.99% down to 0.7µm. Larger sizes of MCPs will be removed more efficiently. For example, *Aspergillus fumigatus* spores, which are found in outdoor air and can cause aspergillosis in hospital patients with immunodeficiency, has a size of about 2.7µm and, for all practical purposes, 100% of these will be removed (the calculated result was 99.999999990%).

7. Effect of filter efficiency on airborne microbial concentrations

7.1 Methods of Calculating the Effect of Filter Efficiency on Airborne Microbial Concentrations in the Supply and Room Air

Shown in Figure 3 is a diagram of a typical ventilation system used in cleanrooms. Large quantities of filtered air are required and, because of the high cost of air conditioning and filtering outside fresh air, about 90% of the air from the cleanroom is recirculated. The recirculated air is mixed with filtered outside air, conditioned, and filtered by high efficiency filters and supplied to the cleanroom.

The number of MCPs that enter a cleanroom through terminal air filters depends on airborne microbial concentrations, air supply rates, and removal efficiency of filters, and is calculated as follows.

Equation 1

MCPs supplied to cleanrooms (number/s) =

$$(C_O.Q_O[1-\eta_O]+ C_R.Q_R)(1-\eta_S)$$

where,

C_O and C_R are the microbial concentrations in the outside and recirculated air (no./m^3), respectively;

Q_O and Q_R are the air supply rates of the outside and recirculated air (m^3/s), respectively;

η_O and η_S are the microbial removal efficiencies of the outside and main supply air filters, respectively.

The filtered supply air enters the cleanroom and mixes with MCPs that are dispersed by personnel at a rate of S_P per second. The cleanroom air is then extracted at low level through grilles round the walls. Deposition onto cleanroom surfaces reduces the concentration of MCPs in the cleanroom air, and the deposition velocity (V_D) of MCPs, with an average equivalent diameter of 12 µm, is 0.0046m/s (Whyte et al, 2012). Deposition will occur on an area equivalent to that of the floor (A_D).

In the steady-state condition there is a mass-balance between the generation of particles and their removal from a cleanroom. By use of a mass balance equation, a solution for the airborne concentration in the room can be obtained, and is given in Equation 2.

Table 4: Smallest sizes of MCP removed at 99.9% and 99.99% efficiency by various filters

Filter code number	Particle removal efficiency at the MPPS	Minimum size of MCP removed with 99.9% efficiency	Minimum size of MCP removed with 99.99% efficiency
HF 0493	11% at 0.42 µm	>5 µm	>5 µm
HF 0533	35% at 0.3 µm	2.0 µm	2.5 µm
HD 2063	87% at 0.22 µm	0.7 µm	0.9 µm
HB 5433	99.15% at 0.2 µm	0.36 µm	0.44 µm
HA 8183	99.987% at 0.22 µm	All sizes*	0.28 µm
HA 8193	99.9988% at 0.22 µm	All sizes*	All sizes*

*All sizes= all microbes between 0.02µm and 50µm

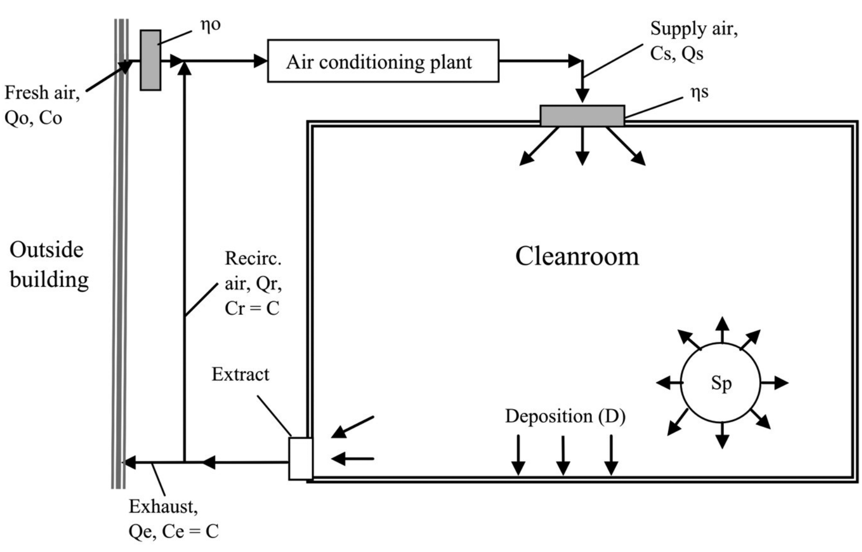

Figure 3: Air supply and extract system in a cleanroom ▭ = air filter. The meanings of the abbreviations are given in the text.

Equation 2

Airborne concentration in non-unidirectional cleanroom (number/m^3) =

$$\frac{C_O.Q_O(1-\eta_O)(1-\eta_S)+S_P}{Q_O+Q_R\eta_S+V_D.A_D}$$

7.2 Effect of Filter Efficiency on the Airborne Microbial Concentration in Cleanrooms

Equation 2 enables the airborne concentration of MCPs in a cleanroom to be calculated when filters of different efficiencies are used. A typical non-unidirectional airflow cleanroom with a floor area of 100m^2 and a height of 3 metres is taken as a practical example. The room had an air supply rate of 3 m^3/s, and hence an air change rate of 36/hour. The air supply was made up of 90% recirculated air, and 10% of fresh air. The microbial concentration of the outside air was taken as 100/m^3 and assumed to have a similar size distribution to that found in the cleanroom (Whyte, 1968). The fresh air was filtered prior to mixing with recirculated air, and therefore the contribution of MCPs from outside air was small. Four people work in the cleanroom and, when wearing cleanroom clothing, their MCPs dispersion rate is assumed to be 3/s per person (Whyte and Hejab, 2007), or 12/s for all four people.

Given in Table 5 are the steady-state concentrations of MCPs in the cleanroom for filter efficiencies that range from 10% to 99.9999% against a size distribution of MCPs. It can be seen that when the filter removal efficiency reaches 99.99% the microbial concentration can be said, for all practical purposes, to be constant. Also, as microbial air samplers will generally not measure below 1/m^3, any further decrease in airborne concentration from the use of a more efficient filter will be about 10,000 times below the measuring capability of an air sampler.

Table 5: Effect of filter efficiency on the airborne microbial concentration in a cleanroom

Filter removal efficiency against MCPs (%)	Airborne microbial concentration per m³ in a cleanroom
10	35.242
20	24.000
50	9.2417
90	3.8558
95	3.6316
99	3.4964
99.9	3.4709
99.99	3.4685
99.999	3.4682
99.9999	3.4682

7.3 Comparison of the MCPs coming from the supply air Compared to those dispersed in the cleanroom

Using the values given in the previous section, Equation 2 can be used to calculate the MCPs supplied by the air supply to the room. This can then be compared to those dispersed in the room. This was carried out on filters with different removal efficiencies, and is given in Table 6. It can be seen that very poor filters allow more MCPs to enter the cleanroom air than are dispersed from personnel, but when the filter efficiency reaches 99%, 99.9% and 99.99%, the proportion of MCPs from the supply air is about 1 in 120, 1280 and 12,800 of those dispersed in the room, respectively.

8. Pressure drop across filters

The pressure drop across filters investigated in this article is given in Table 7. It can be seen that the pressure drop of a filter with a removal efficiency of 87% against the MPPS is 6 to 8 times less than that across filters commonly used in cleanrooms i.e. those with a removal efficiency of 99.987% or 99.9988%.

Table 7: Pressure drop across filter media

Particle removal efficiency at MPPS	Expected pressure drop (Pa) at 5.3 cm/s
11%	34
35%	34
87%	145
99.15%	311
99.987%	883
99.9988%	1177

9. Discussion and conclusions

The object of this investigation was to ascertain the removal efficiency of filters against MCPs in the supply air to cleanrooms. Most of the air in cleanrooms is recirculated, and the air to be filtered will have a size distribution of MCPs similar to that found in the room air. As discussed in Section 6.1, the MCPs found in occupied rooms are dispersed from personnel and have an average equivalent diameter of about 12 µm. Air filters will therefore be much more efficient in removing MCPs than sub-micrometre particles of the ≥0.3 µm or ≥0.5 µm type. The MCPs in the outside air have a similar size distribution, but as fresh air is a minor part of the air supply, and the air is normally filtered before being mixed with recirculated air, this contribution to room air is very small.

It is not possible to measure the efficiency of high efficiency filters *in situ*, as microbial air samplers are not sensitive enough to measure the very low microbial concentrations that penetrate high efficiency filters. This article therefore reports a method by which the size distribution of the MCPs to be filtered, and a filter's calculated efficiency against known particle diameters, are used to obtain the filter's removal efficiency. The particle removal efficiency of a range of filters was obtained and it was found that a filter 87% efficient in removing the MPPS (as classified according to EN 1822) gave an overall removal efficiency against MCPs of greater than 99.99%.

The likely airborne microbial concentration in the air of a typical cleanroom during manufacture was calculated for a range of filters. As the filter efficiency increased, the airborne MCPs in cleanroom air decreased until, at a removal efficiency of 99.99%, a minimum was reached where, for all practical purposes, the airborne concentration was constant, and any further increase in filter efficiency would give a decrease in the airborne concentration that was about 10,000 times less than the measuring ability of a microbial sampler.

A calculation was carried out to compare the contribution of MCPs from the filtered air supply to that dispersed into cleanroom air. It was found that the air supply passing through air filters with an efficiency of 99.9% and 99.99% against MCPs, contributed about 1 in 1280 and 1 in 12,800, respectively, to the total number of MCPs in room air.

Summarising the conclusions with respect to filter efficiency, it would appear that a filter 90% efficient, as classified by the standard test method (EN 1822), would give a removal of at least 99.99% of MCPs supplied to a cleanroom and ensure that the contribution of microbial contamination from the supply air is insignificant and immeasurable. Should it be necessary to reduce the airborne microbial concentration in a cleanroom, more effective measures should be employed. This can be achieved by either reducing the dispersion of MCPs by minimising the number of personnel in the cleanroom and using more efficient cleanroom clothing, or by increasing the dilution of the airborne contamination by increasing the air supply volume.

The main reason for this investigation was to investigate the filter efficiency required to remove the MCPs found in recirculated air prior to being supplied to a cleanroom. However, there are situations where a filter's removal

Table 6: The effect of filter efficiency on the proportion of microbes coming from supply air

Filter removal efficiency against MCPs (%)	MCPs in filtered air supply (no./s)	MCPs dispersed by personnel (no/s)	Ratio of MCPs from supply air to those dispersed in room
10	109.93	12	9.2:1
50	19.976	12	1.7:1
90	1.3411	12	1:8.9
99	0.0974	12	1:123
99.9	0.0094	12	1:1276
99.99	0.000937	12	1:12810
99.999	0.000094	12	1:128100

efficiency against a single species of microbes with a known size may be required. The minimum sizes of microbes that are removed at 99.9% and 99.99% efficiency by a range of high efficiency filters has been calculated and given in this article, so that the correct filter can be selected. This information can be used in situations, such as hospitals, where outside air is used as the source of air to avoid recirculation of high concentrations of pathogenic microbes. However, outside air contains *Aspergillus fumigatus* spores which may cause aspergillosis in patients with immunodeficiency, and an air filter with a removal efficiency of 90% at the MPPS can be calculated to give a removal efficiency of practically 100%, and appears to be suitable for hospital areas where aspergillus spores are considered a problem.

If a filter is used that is suitable for effective MCPs removal i.e. one that is 90% efficient against EN 1822, then this will have a pressure drop about 6-8 times less than filters typically used in cleanrooms to remove sub-micrometre particles. Using such lower-pressure filters will result in a substantial drop in energy consumption and cost of running a cleanroom.

1. Brown RC (1993) "Air filtration: An integrated approach to the theory and applications of fibrous filters", Elsevier Science.
2. Davies CN: (1973). "Air filtration", Academic Press.
3. Davies RR and Noble WC: (1962). "Dispersal of bacteria in desquamated skin", *Lancet*, **ii**, pp1295-1297.
4. Dhaniyala S and Liu BYH: (1999A)."Investigations of particle penetration in fibrous filters Part 1. Experimental". *Journal of the IEST*, January/February, pp32-40.
5. Dhaniyala S and Liu BYH: (1999B). "Investigations of particle penetration in fibrous filters Part II. Theoretical", *Journal of the IEST*, March/April, pp40-46.
6. EN 1822, Parts 1 to 5: (2009). "High efficiency air filters (EPA, HEPA and ULPA)". European Committee for Standardization.
7. Hinds WC: (1999). "Aerosol technology – properties, behaviour, and measurement of airborne particles", second edition. Wiley – Interscience, New York, USA.
8. Kowalski WJ, Bahnfleth WP and Whittam TS: (1999). "Filtration of airborne microorganism: modelling and prediction". *ASHRAE Transactions: Research*, **105**, (2), pp4-17.
9. Matsuki M and Tanaka N: (1998). "Energy saving system for air conditioning of clean room for semiconductor factory (estimate of FMU system)". *Oki Technical Review*, **63**, pp49–52.
10. McIntosh C, Lidwell OM, Towers AG and Marples RR: (1978). "The dimensions of skin fragments dispersed into the air during activity", *Journal of Hygiene, Cambridge*, **81**, pp471-479.
11. Noble WC, Lidwell OM and Kingston D: (1963). "The size distribution of airborne particles carrying micro-organisms". *Journal of Hygiene, Cambridge*, **61**, pp385-391.
12. Schicht HH: (1999). "Cost efficiency and energy saving concepts for cleanrooms". In Cleanroom Design – Second Edition, edited by W Whyte, pp141-155.
13. Tschudi B, Sartor D and Xu T: (2001). "An energy efficiency guide for use in cleanroom programming". Report LBNL-49223, Lawrence Berkeley National Laboratory, Berkeley, USA.
14. Whyte W: (1968). "Bacteriological aspects of air conditioning plant", *Journal of Hygiene, Cambridge*. **66**, pp567-584.
15. Whyte W and Bailey PV: (1985). "Reduction of microbial dispersion by clothing". *Journal of Parenteral Science and Technology*, **39**, (1), pp51-61.
16. Whyte W: (1986). "Sterility assurance and models for assessing airborne contamination". *Journal of Parenteral Science and Technology*, **40**, (5), pp188-197.
17. Whyte W and Hejab M: (2007). "Particle and microbial airborne dispersion from people", *European Journal of Parenteral & Pharmaceutical Sciences*, **12**, (2), pp39-46.
18. Whyte W, Green G and Whyte W M: (2012). "Removal of Microbe-Carrying Particles by High Efficiency Air Filters in Cleanrooms", *International Journal of Ventilation*, **10**, (4), pp 339-351.

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