A Review of Assigned Protection Factors of Various Types and Classes of Respiratory Protective Equipment with Reference to their Measured Breathing Resistances

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The British Standards Institution 'Guide to implementing an effective respiratory protective device programme' (BS 4275) lists assigned protection factors (APFs) for various types of respiratory protective equipment (RPE). The APFs were allocated either on the basis of available workplace studies data which met set criteria or on the basis of professional judgement that there is equivalence between its operation and that of a device for which an APF is derived from workplace data. However, in many cases no workplace study information exists to support this professional judgement. As an interim measure, pending information based on workplace measurements, the breathing resistance of a range of tight-fitting RPE from negative pressure filtering devices through to self-contained positive pressure breathing apparatus was measured at various breathing rates. The relative inhalation resistances were then compared on the assumption that similar breathing resistance performance is likely to give similar inward leakage on a facepiece and hence similar protection if all other factors, such as fit, etc., are equal. This work indicates that for most devices the allocation of APFs by analogy to other devices seems to be acceptable. However, there appears to be no justification for the allocation of an APF value of 100 to continuous flow compressed air line breathing apparatus. It is recommended that it should be lowered to 40 until there is valid workplace study data to support the current APF of 100. The work provides an informative insight into the relative performance of devices.

Keywords: assigned protection factors; breathing apparatus; breathing resistance; respirators; respiratory protective equipment

INTRODUCTION

The performance of respiratory protective equipment (RPE), and in particular the level of protection it provides when worn in the workplace, is a complex subject. This is because of the interaction of many factors, such as the degree of its fit to the wearer, its adequacy for the air contaminant(s) and the environment, the task, the degree of training of the wearer and whether or not it is properly maintained and correctly used.

When measurements of the level of workplace protection of RPE are undertaken, then other factors which relate to the test protocol, such as sampling/analysis and interpretation of the results, can come into play (Johnston *et al.*, 1992; Myers and Hornung, 1993; Nelson, 1995, 1996). These can affect the result and the overall conclusion. Thus, it can be seen that to allocate a single protection factor value to a particular type of RPE requires a rigorous approach to its measurement and a good deal of validated data. For the protection to be achieved and maintained at all times it is necessary that the RPE functions properly and is worn and used correctly by trained and fit-tested users.

One of the best ways to obtain performance data is via properly conducted workplace studies which measure inward leakage of the workplace contaminant into the facepiece of the RPE. Such studies are expensive and require the cooperation of the work-

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force and management as well as expertise in sampling techniques, etc.

British Standard BS 4275 'Guide to implementing an effective respiratory protective device programme' (British Standards Institution, 1997) currently lists what it terms an 'assigned protection factor' (APF) for the various types and classes of RPE. According to BS4275, these APFs represent the best estimates and assumptions from the available data gathered on workplace measurements or from what the Standard describes as 'professional judgement'. The workplace data used were from tests having, among other criteria, a validated and appropriate sampling protocol. The Standard gives a description of the basis for choice or elimination of data, which was examined in preparing the APFs.

However, for many types of RPE no workplace protection factor data exist. Here, the Standard explains that an APF has been ascribed to a type of device (e.g. unassisted fresh air hose breathing apparatus) on the basis of equivalence between its operation and that of a different type of device for which an APF is derived from workplace data. This procedure has been used for the majority of breathing apparatus (BA) and often by analogy to filtering devices. This professional judgement approach, while probably sound in most cases and the product of many years experience, has little, if any, technical data to support the decisions taken.

By comparing laboratory generated data on breathing resistance, and in particular inhalation resistance, i.e. the negative pressure inside the mask on inhalation, the reliability of the present system of allocation of APFs can be supported, or otherwise, until such time as sufficient workplace data becomes available.

Background

The purpose of this work was to obtain laboratory generated data on breathing resistance, and in particu-lar inhalation resistance, of various types of RPE when subjected to varying breathing rates and breathing patterns either employed in European Standard tests or based on those recorded on an actual user. Based on this information, an estimate of the relative performance of the devices can be obtained by comparing the inhalation resistance of the types of RPE described in BS 4275, tables 6 and 7. At the same time a comparison can be made between the types of RPE for which an APF has been allocated on the basis of workplace data (the benchmark devices) and those types of devices whose APFs have been deemed equivalent to the benchmark device by experience and judgement.

Thus, in the context of BS 4275, it may be sensible to justify the equivalence of an RPE to its benchmark reference device if the breathing resistance performances are similar. Equally, it might be difficult to justify any equivalence when the breathing resistance, and particularly the inhalation resistance, is markedly higher than that of the benchmark device.

Table 1 contains information extracted from tables 6 and 7 of BS 4275. It shows all the benchmark equipment that employ full face masks, their APFs on the basis of workplace data and the devices deemed 'equivalent'.

An example of this equivalence is given in item 2 of Table 1. Negative demand respirators consisting of a full face mask and a high efficiency particle filter are used as the benchmark apparatus. They are given an APF of 40 based on workplace data. The Standard states (Annex D, clause D.1.3) that unassisted fresh air hose full face mask and negative demand air fed BA for which workplace data do not exist are judged equivalent to this benchmark device and are therefore also given an APF of 40.

BS 4275 clause D.1.3(b) also states 'The performance of a power assisted and powered fresh air hose and compressed air line device would be the same as

Table 1. Table of 'benchmark' and 'equivalent' RPE employing a full face mask and their assigned APFs as stated in BS 4275 Annex D1.3 and tables 6 and 7

	Benchmark apparatus with full face mask	APF	Equipment selected as 'equivalent'
1	Negative pressure respirator with gas or combined filter	20	
2	Negative pressure respirator with P3 particle filter (FFMP3)	40	Negative demand air fed (compressed air line negative demand valve BA; CADV)
			Unassisted fresh air hose BA (UFAH)
3	Power assisted respirator, TM 3, with gas or combined filter or particle filter (PAR)	40	Assisted fresh air hose (AFAH)
			Compressed air line devices[a] (CF)
4		100	Compressed air line FFM (continuous flow compressed air line BA; CF)
5	Self-contained negative pressure demand valve BA (SCBA NP)	40	
6	None	2000	Self-contained positive pressure demand valve BA (SCBA PP)

[a]Compressed air line devices are selected as equivalent devices to power assisted respirators in BS 4275 but are actually given an APF of 100 in BS 4275, table 7.

for the corresponding powered filtering devices fitted with a high efficiency filter and the same facepiece.' However, this does not appear to be the case in table 7 of BS 4275. Here a continuous flow compressed air line BA with full face mask is given an APF of 100 instead of the APF of 40 given to the stated benchmark device (see items 3 and 4 in Table 1).

Rationale

The protection afforded by tight-fitting facepiece devices, such as respirators incorporating a full face mask, rely to a great extent on the effectiveness of the face seal. It is logical to argue that, if a face mask is subjected to a negative pressure in the mask cavity due to the wearer's breathing effort, then the greater that pressure (i.e. the more negative), the more likely is the face seal to allow leakage into the breathing zone. An increase in the pressure differential across an existing face seal leak site of fixed geometry is also likely to increase the leakage. The extent of face seal leakage governs to a great extent the protection afforded by the RPE, all other things being equal.

Campbell (1984) presented a theoretical model which describes how the protection factor of a given respirator is affected by a change in the breathing resistance as a result of a corresponding change in filter resistance. The model predicts that the protection factor will decrease as the pressure drop across the facepiece increases.

Hack *et al.* (1980), in a series of quantitative fit tests on supplied air devices, found that the protection factors increased as the air flow rate to the device increased. Increasing the air flow rate to the device will result in reducing the difference between wearer's demand for air and the air flow rate to the device, thus reducing the inhalation resistance. Hack *et al.* also measured inward leakage of up to 6% for a test subject who was able to create negative pressure inside a face mask of a continuous flow respirator during heavy deep breathing.

Nelson and Colton (2000) showed that an increase in the breathing resistance resulted in an increase in face seal leak rate into a face mask and hence an increase in face seal leakage. An increased face seal leak rate of a factor of four was recorded with an increase in breathing resistance of 14 mmH_2O (0.14 kPa) (i.e. from 5.6 to 19.6 mmH_2O). The level of increase in peak inhalation resistance measured in our study was, for some types of RPE, substantially greater than the breathing resistances employed in the Nelson and Colton study.

Vaughan *et al.* (1994), in a study of particle penetration into respirators through leaks of known geometry, concluded that greater leakage through a face seal leak will result from an increase in the pressure differential across the leak site

Peak inhalation resistance values (i.e. the inhalation value measured at the peak breathing rate during the inhalation phase of the breathing cycle) may not be the decisive factor which governs the amount of leakage into the face mask. Other factors may also come into play, such as the length of time a negative pressure is maintained within the face mask. A device that has a negative peak inhalation that quickly recovers owing to an appropriate air supply may be less susceptible to inward leakage than a device that has perhaps a less negative peak but maintains negative pressure for a longer period.

MATERIALS AND METHODS

Breathing waveforms

Breathing resistance measurements in most European Standards for RPE employ the use of sinusoidal breathing waveforms with minute volumes of 30 and 50 l/min. These minute volumes are supposed to represent light/medium and medium/heavy work rates (~150–300 kcal/h), though in practice the work rate employed on a particular task depends greatly on the physiology, fitness, age, etc., of the RPE wearer and can result in lower or higher work rates between different subjects. It was proposed, therefore, that the breathing waveforms employed in this study were the standard 30 l/min (1.5 l/stroke × 20 strokes/min) and 50 l/min (2.0 l/stroke × 25 strokes/min) waveforms, as the majority of RPE types are subjected to these tests, and an additional breathing waveform (an actual user breathing waveform) intended to represent that from a workplace scenario.

Generation of a user breathing waveform

A test subject donned a pressure probed full face mask to which a 'filter simulator' was fitted [the 'filter simulator' is defined in European Standard EN 136 (European Committee for Standardization, 1998) and is designed to simulate the maximum breathing resistance and weight of filters permitted for direct connection to a full face mask with a thread complying with EN 148-1 (European Committee for Standardization, 1999)]. The subject was then asked to exercise, i.e. walk, bend and breathe deeply. The pressure within the breathing zone of the face mask was measured and logged on a data acquisition system over a number of breathing cycles. A single representative waveform was then derived from the sampled data and fed into a computer controlled variable waveform breathing machine (VWBM). The representative repeating waveform could then be reproduced by the VWBM for use in the study. Figure 1 shows the user breathing waveform in-mask pressure trace and the resultant output waveform generated from the VWBM. Figure 1 also demonstrates how well the VWBM generated waveform matches the profile of the user breathing waveform.

The original user breathing waveform sampled contained a natural pause in the breathing cycle. The
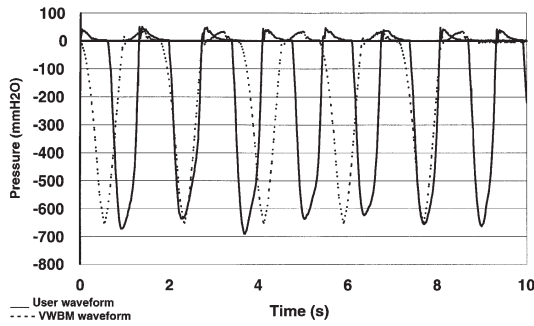
Fig. 1. User breathing waveform and VWBM generated waveform.
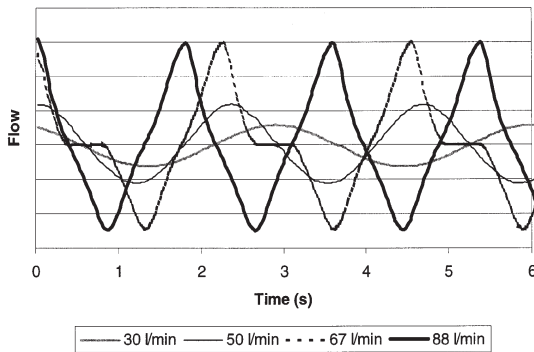
Fig. 2. Breathing waveforms presented on a common air flow rate scale.

overall minute volume of this waveform was 67 l/min (~2.6 l/stroke × 26 strokes/min). This pause was removed to create the fourth and final waveform used in this study with a minute volume of 88 l/min (2.6 l/stroke × 34 strokes/min). All four waveforms employed are shown in Fig. 2, plotted on a common scale.

Experimental procedure

It is generally easier to carry out tests on devices fitted with full face masks than with hoods or visors because masks can be fitted securely to the test apparatus in a leak-tight and fairly reproducible manner. The movement of hoods in sequence with the breathing rate or the looseness of fit of a lightweight visor seal makes reproducibility more problematical. For this reason, and since comparison of results from different devices is the essence of this work, each being compared with a benchmark device, and all devices need to be fitted and removed from the dummy head a number of times, the work has concentrated on tests on equipment fitted with a full face mask. This category of equipment potentially has the highest APF values and has a high proportion of devices for which there is no workplace protection data.

The test procedure used was essentially that of well-established breathing resistance tests which are described in European Standards for RPE (e.g. EN 136). These are performed on a breathing simulator connected to a 'Sheffield dummy head' which is fitted with concentric breathing tubes. The general arrangement of the dummy head is shown in Fig. 3. Air is exhaled through the outer tube and inhaled through the inner tube, the sequence being controlled by a series of solenoid valves. The face mask of the RPE under test was fitted in a leak-tight manner and appropriate in-mask pressure measurements were made using a pressure probe, as defined in the relevant European Standards. Pressure measurements were made with a Furness Controls micromanometer (Bexhill-on-Sea, Sussex, UK), connected to a data acquisition system sampling at 20 Hz.

Because these tests employed a wider range of breathing waveforms than the normal European Standard tests and because the tests were intended to represent
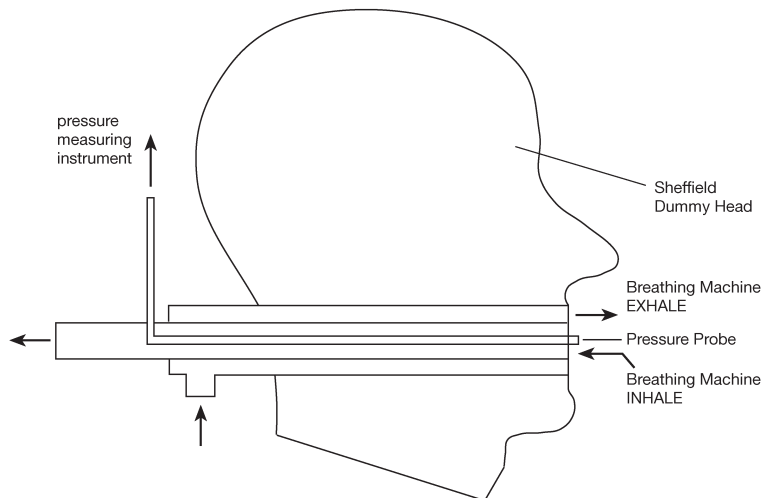
Fig. 3. Sheffield dummy head.

Table 2. Maximum breathing resistance values for various types of RPE at various breathing rates

| RPE type | RPE Ref. | Maximum breathing resistances at various breathing machine settings (mmH$_2$O) | | | | | | | |
| | | 30 l/min | | 50 l/min | | 67 l/min | | 88 l/min | |
		Inh	Exh	Inh	Exh	Inh	Exh	Inh	Exh
Full face mask with P3 filter	FFM	−31.1	19.1	−56.0	29.5	−131.1	83.1	−131.1	83.1
Power assisted respirator	PAR 1	0.4	16.1	−13.0	21.5	−49.8	37.7	−49.8	37.5
Power assisted respirator	PAR 2	0.2	15.1	−17.6	21.5	−97.3	46.1	−97.6	45.6
Power assisted respirator	PAR 3	0.4	18.8	−7.9	29.6	−86.8	78.5	−81.2	78.7
Unassisted fresh air hose	UFAH 1	−29.6	13.8	−61.2	29.5	−177.7	77.9	−178.4	76.4
Unassisted fresh air hose	UFAH 2	−31.0	6.4	−66.0	11.6	−165.1	44.4	−165.9	44.4
Assisted fresh air hose	AFAH 1	3.1	29.1	−6.7	37.5	−61.5	79.5	−59.6	82.9
Assisted fresh air hose	AFAH 2	19.0	59.2	9.4	73.4	−4.7	118.0	−3.2	118.0
Continuous flow compressed air line BA	CF 1	0.4	15.4	−99.0	20.3	−940.0	51.3	−940.0	51.3
Continuous flow compressed air line BA	CF 2	0.9	33.8	−1.6	50.0	−920.4	105.0	−839.8	105.0
Continuous flow compressed air line BA	CF 3	−1.3	18.1	−16.2	29.6	−659.0	70.2	−702.0	72.7
Compressed air line negative demand valve BA	CADV	−43.0	20.0	−56.3	30.4	−100.0	79.5	−90.0	79.5
Self-contained BA negative demand	SCBA NP	−44.0	15.0	−50.0	22.0	−64.0	52.0	−66.0	53.0
Self-contained BA positive pressure	SCBA PP	14.0	68.0	14.0	72.0	9.0	88.0	9.0	88.0

a workplace scenario involving the wearer breathing at different rates, three breathing machines were employed; one operating at 30 l/min sinusoidal, one operating at 50 l/min sinusoidal and the third a VWBM operating at either 67 or 88 l/min. The three breathing machines were connected via valves so that each RPE could be instantly subjected to a different waveform as breathing machines were switched in and out of the circuit.

The measurements were conducted with the given RPE operating at the manufacturers' minimum design condition (MMDC) or manufacturers' minimum design flow (MMDF), whichever was appropriate. The MMDC or the MMDF was used as a common baseline from which to compare the relative performances of the devices. MMDC or MMDF is a legitimate operational condition of use for the device and is also the condition at which certain tests are carried out to assess its compliance with European Standards. The types and numbers of tight fitting RPE employed in this work are shown in Table 2.

RESULTS AND DISCUSSION

The breathing resistance values recorded are tabulated in Table 2 and shown graphically, grouped together as benchmark and equivalent devices, in Fig. 4.

Assessment criteria

A possible workplace scenario is where the RPE wearer carries out tasks where the work rate can vary
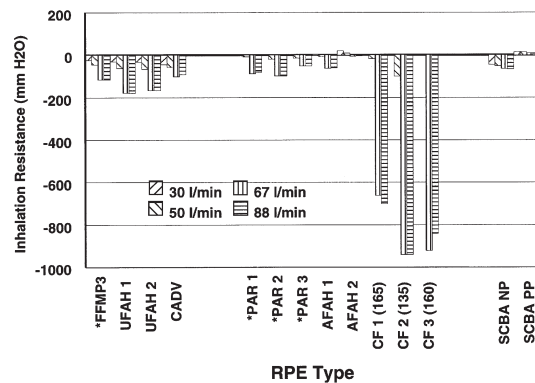

Fig. 4. Inhalation resistance of devices at various breathing rates. The RPE are grouped as 'benchmark'* and 'equivalent' devices as shown in Table 1 (where appropriate).

from sedentary through to medium and on to heavy. The time periods for each work condition will depend on the job and on the wearer's physical condition. A degree of self-regulation will take place and the wearer's physical condition will automatically limit the time and effort. If the RPE is not, however, capable of accommodating the wearer's breathing demands then the device will impose an extra breathing load on the wearer. This may induce increased leakage due to the increased negative pressure in the face mask. It is this sort of situation that we have tried to simulate in these tests.

As stated earlier, the tests have been carried out at the MMDC (or MMDF) for the equipment because this is a legitimate operational condition of use of the

device and is also the condition at which a device is assessed in European Standards; for instance, a power assisted respirator incorporating a full face mask is required to meet the relevant class requirements (e.g. inward leakage, breathing resistance, etc.) at the minimum flow rate as specified by the manufacturer, e.g. 120 l/min. It is assumed that the APF allocated to a device will apply to the device operating under this condition, otherwise the APF would vary with the operational set-up of the device. Conditions of operation would need to be placed on the APF, which is not the case in BS 4275.

Full face mask negative pressure respirator with high efficiency particulate filter and equivalent devices

The breathing resistance characteristics for this benchmark apparatus, i.e. a full face mask with high efficiency particulate filter (FFM), and the adjudged equivalent unassisted fresh air hose (UFAH) and compressed air line negative demand valve (CADV) BA are shown in Fig. 5a–d. Figure 5a shows that at 30 l/min sinusoidal breathing rate, negative demand air line inhalation resistance tends to peak at ~10 mmH$_2$O greater than the benchmark device, the negative pressure respirator. It is suggested that at this breathing rate and for this relatively small increase in negative pressure it will be difficult to judge whether this has an effect on the APF.

At a breathing rate of 50 l/min there is still little difference in all the devices and, based on this, the decision to equate the devices looks well justified. Figure 5b shows that the exhalation resistance of all devices is within the maximum 30 mmH$_2$O allowed in the relevant European Standards (European Committee for Standardization, 1994a,b, 1998).

Figure 5c,d begins to show differences between various devices. It can now be seen that in the case of the CADV device, once the demand valve has opened at approximately –70 mmH$_2$O, air is rapidly supplied to the face mask and the inhalation resistance is kept relatively low, certainly lower than the benchmark device with which it has been compared. The UFAH now shows the highest inhalation resistance, though here again whether the difference in inhalation resistance between it and the benchmark apparatus is significant in terms of allocation of APFs is difficult to say. The exhalation resistances of the devices are again similar. Whilst the UFAH imposes the highest inhalation resistance of the three devices, it is still reasonable to suggest that the equivalence holds. It is also worth noting that in this situation the negative demand respirator and the UFAH will impose a much higher physiological load on the wearer than the CADV BA, since in this mode it is this latter device which is now supplying air at a volume of the order of the breathing rate. This is clearly not the case in the two unassisted devices. In this scenario, the self-

regulation mentioned earlier is likely to come into play to limit the wearer's work rate using these two devices.

Power assisted respirator and equivalent assisted fresh air hose

Breathing resistance traces for these devices are shown in Fig. 6a–d. It must be assumed that an APF of 40 applies to the benchmark power assisted respirator (PAR) having the highest inhalation resistance of the three PARs. This device was compared with the performance of the assisted fresh air hose device (AFAH) having the highest inhalation resistance, thus showing the worst case situation. As Fig. 6 shows, the fresh air hose device always exhibits less peak inhalation resistance than that of the benchmark device.

Also in each case, as Table 2 shows, the worst performing AFAH was roughly equivalent to the best performing PAR and the best performing AFAH was considerably better than the best performing PAR. The conclusion, therefore, is that based on comparison of inhalation resistances the equivalence of the AFAH to the PAR is justified

The performance of the AFAH devices is related to their relatively high minimum design air flow rates; these were 290 and 350 l/min for the devices measured in this study. In both devices an overflow valve is provided to dump excess air, but as Fig. 6 shows, the exhalation resistance of these devices is approximately twice that of the PAR, which might give a wearer some discomfort in the long term. The airflow control arrangements for these devices are on the blower units, which when in use may be up to 9 m away from, not with, the wearer.

Continuous flow compressed air line BA

As Table 1 shows, and as described earlier, although in the text of BS 4275 continuous flow compressed air line BA were assumed to be equivalent to a PAR, they have been allocated an APF of 100 in table 7 of BS 4275. For the purposes of this work a comparison has been made between these devices and the other air line device assessed (i.e. the CADV) on the basis that this type of device might well be employed in similar types of workplace activities. Three continuous flow devices, referred to as CF 1, CF 2 and CF 3, having minimum design flows of 135, 160 and 165 l/min, respectively, were tested. The breathing resistance traces for the continuous flow compressed air line BA with the lowest minimum design flow of 135 l/min (CF 1) and a CADV BA are shown in Fig. 7a–d.

With the flow set to 135 l/min the performance at 30 l/min sinusoidal breathing rate as shown in Fig. 7a is not surprising, since the peak instantaneous flow of a 30 l/min sinusoidal breathing rate is ~95 l/min. Hence, there are no negative values shown on inhalation. The
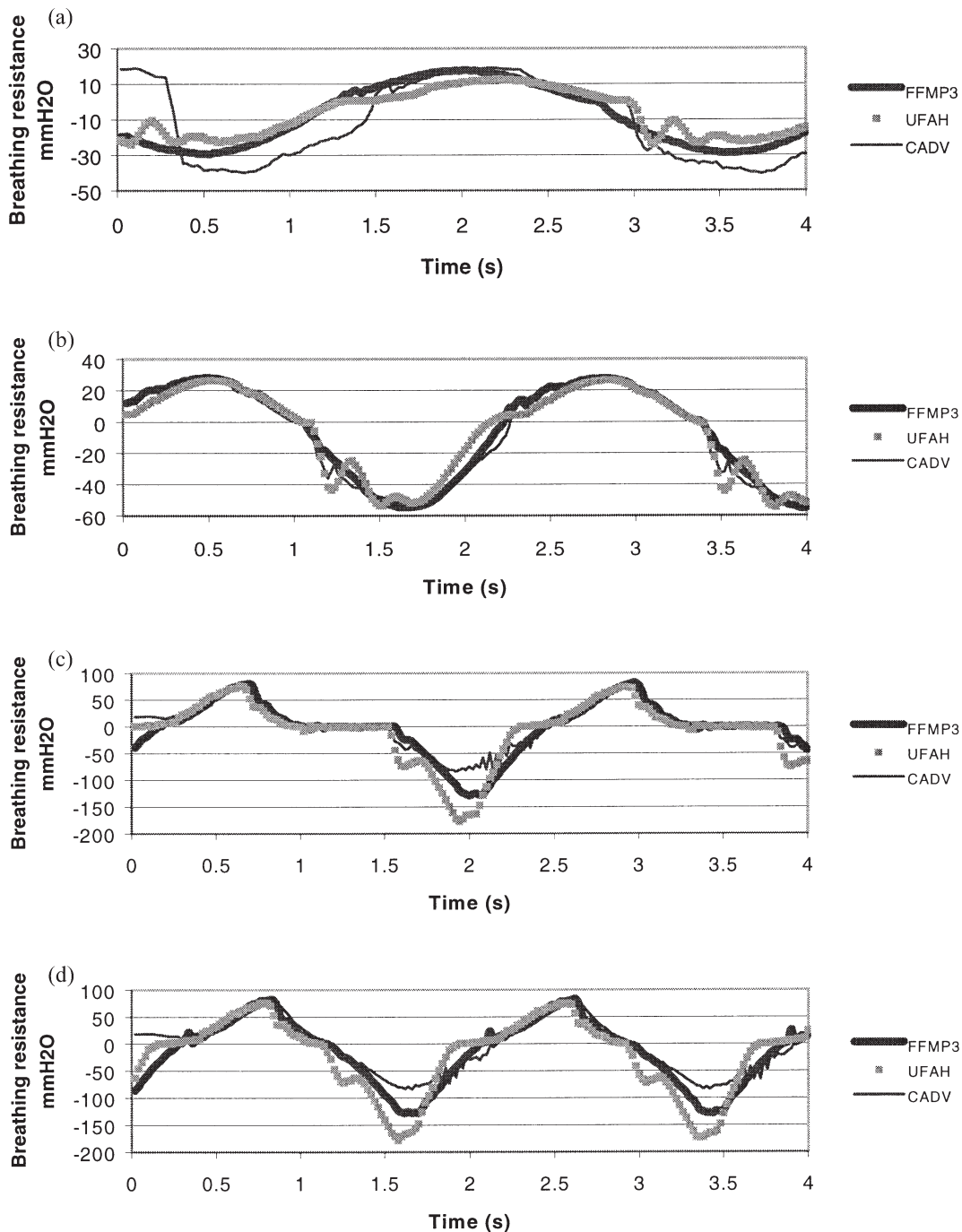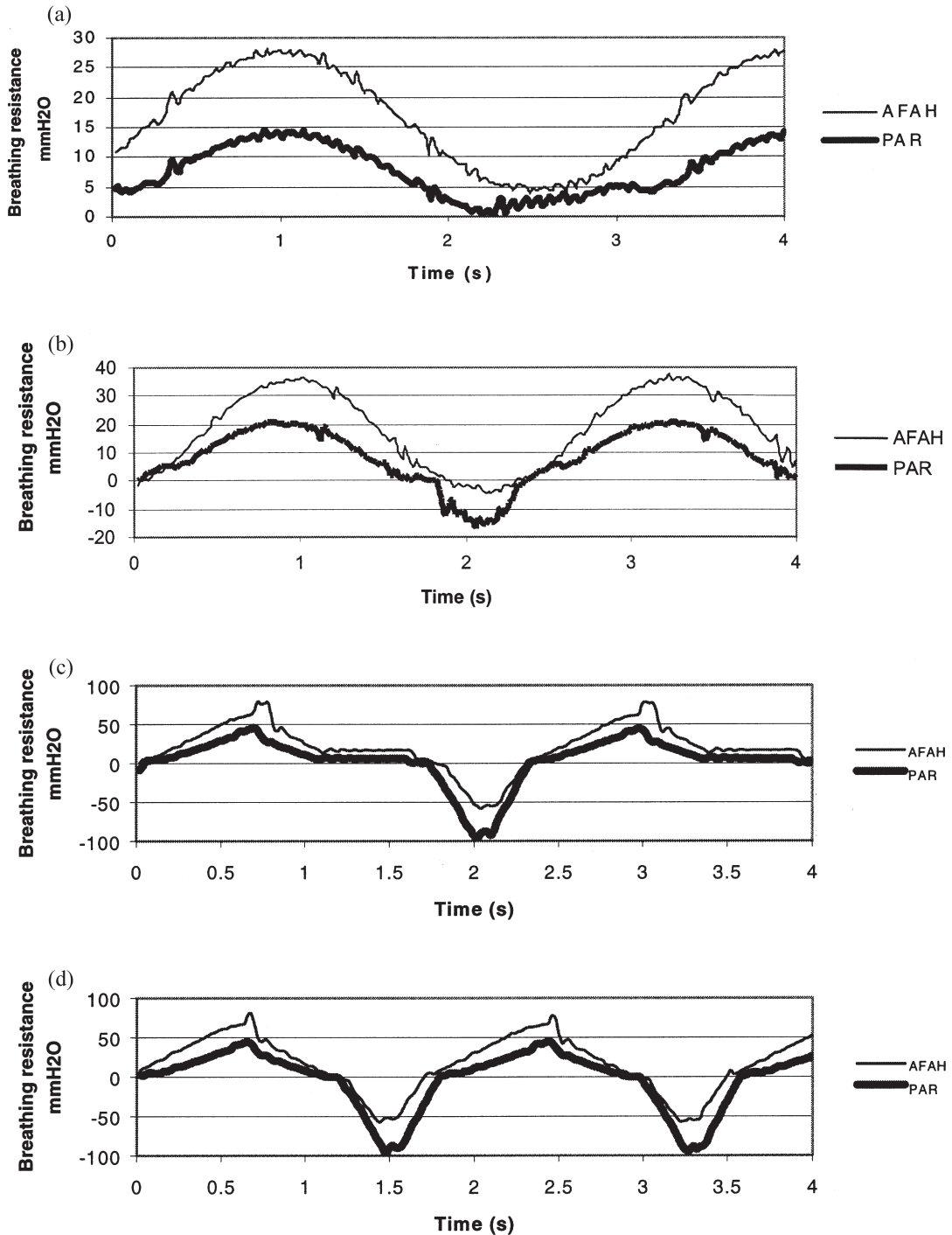
Fig. 5. Breathing resistance waveforms at various breathing rates for the negative pressure respirator (FFMP3), unassisted fresh air hose (UFAH) and compressed air line negative demand valve BA (CADV). (a) 30 l/min (1.5 × 20) sinusoidal breathing rate; (b) 50 l/min (2.0 × 25) sinusoidal breathing rate; (c) 67 l/min (2.6 × 26) non-sinusoidal breathing rate; (d) 88 l/min (2.6 × 34) non-sinusoidal breathing rate.

performance of the CADV is as previously shown, with a negative peak of approximately –40 mmH$_2$O.

The picture changes slightly in Fig. 7b, showing a sinusoidal breathing rate of 50 l/min. The inhalation

resistance value has increased considerably for the continuous flow air line. This is because at 50 l/min sinusoidal the peak instantaneous flow rate is ~160 l/min, so we now see negative pressure building
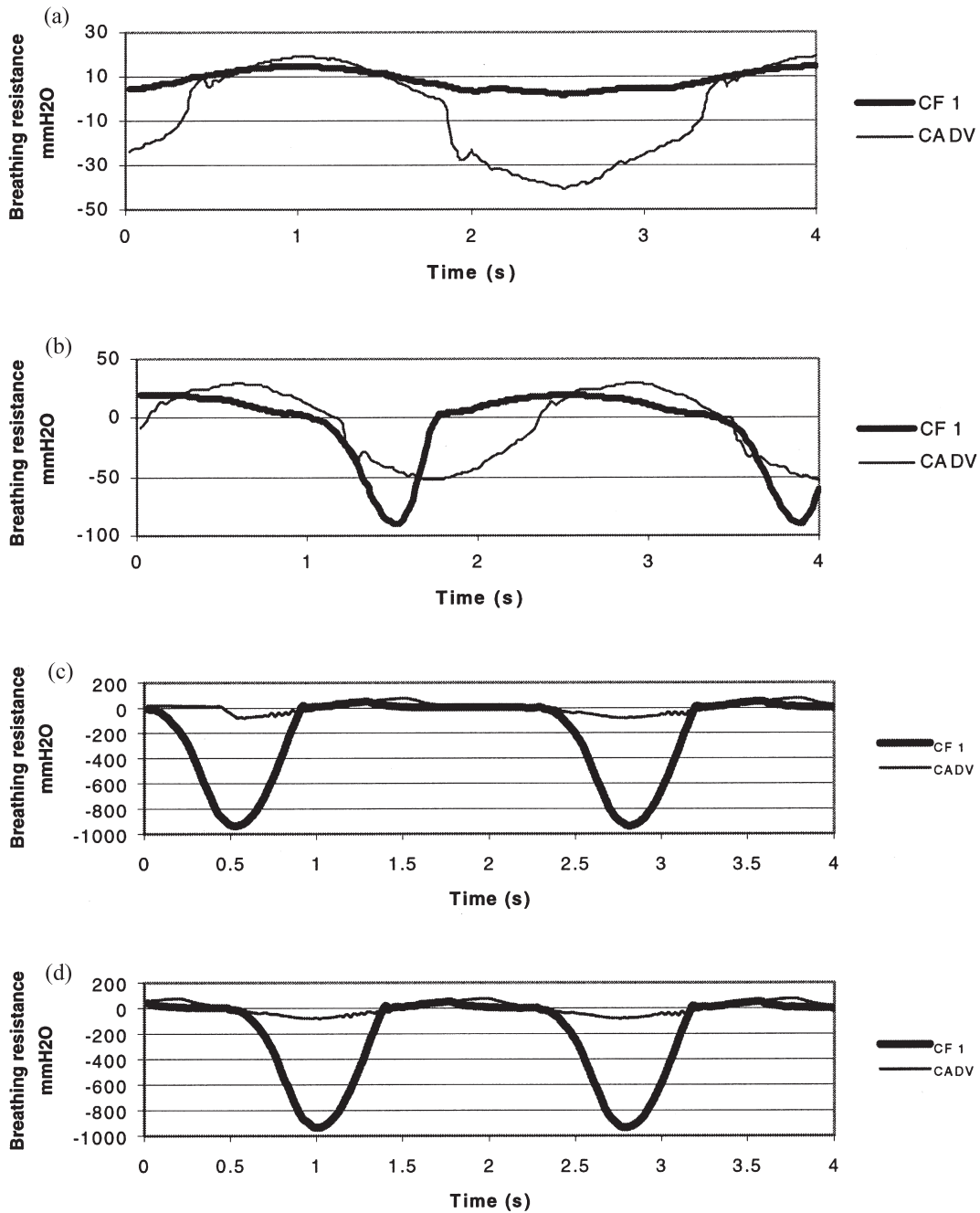
Fig. 6. Breathing resistance waveforms at various breathing rates for the power assisted respirator (PAR 1) and assisted fresh air hose respirator (AFAH 1). (a) 30 l/min (1.5×20) sinusoidal breathing rate; (b) 50 l/min (2.0×25) sinusoidal breathing rate; (c) 67 l/min (2.6×26) non-sinusoidal breathing rate; (d) 88 l/min (2.6×34) non-sinusoidal breathing rate.

up inside the mask due to a period when the breathing rate exceeds the supply flow rate. The CADV device has increased its inhalation value by a small amount.

Figure 7c shows the performance at a minute volume of 67 l/min, equating to a peak instantaneous flow of ~180 l/min. At this breathing rate there is serious negative pressure being applied within each face mask of all three continuous flow devices, the magnitude of the pressure drop being greater with a lower minimum design flow rate. This pattern is
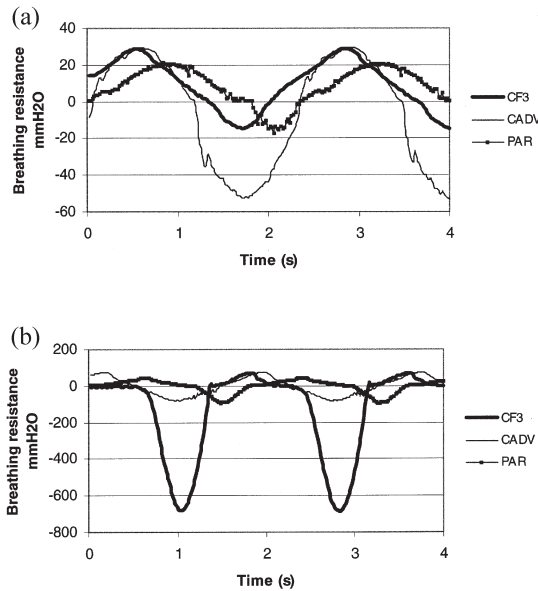
Fig. 7. Breathing resistance waveforms at various breathing rates for one continuous flow compressed air line (CF 1) and a compressed air line negative demand valve BA (CADV). (a) 30 l/min (1.5 × 20) sinusoidal breathing rate; (b) 50 l/min (2.0 × 25) sinusoidal breathing rate; (c) 67 l/min (2.6 × 26) non-sinusoidal breathing rate; (d) 88 l/min (2.6 × 34) non-sinusoidal breathing rate.

repeated at the higher minute volume of 88 l/min, as shown in Fig. 7d. However, it can be seen that the CADV device is performing very much as it does at lower breathing rates, with a maximum peak inhalation of ~100 mmH$_2$O.

A second comparison was also made between the benchmark PAR, a CADV BA and a continuous flow compressed air line BA. CF 3, which had the highest minimum design flow rate of 165 l/min was used in this comparison. This is shown in Fig. 8a,b. As Fig. 8a indicates, at a sinusoidal breathing rate of

(a)

(b)

Fig. 8. (a) Breathing resistance waveforms for benchmark PAR and 'equivalent' devices. Constant flow air line (CF 3) and compressed air line negative demand valve (CADV) at a sinusoidal breathing rate of 50 l/min (2.0 × 25). (b) Breathing resistance waveforms for benchmark PAR and 'equivalent' devices. CF 3 and CADV BA at a non-sinusoidal breathing rate of 88 l/min (2.6 × 34).

50 l/min the inhalation value of the CF device is very similar to the PAR; at this breathing rate the CADV displays the highest inhalation resistance. However, at the breathing rate of 88 l/min, as Fig. 8b shows, the CF device exhibits a very large inhalation resistance when compared to its benchmark PAR device and to the CADV.

It is commonly understood that in RPE dependent on a continuous flow of air to the face mask, when the breathing rate requirement exceeds the air flow supply the pressure within the face mask will become negative. The bigger the difference between air supply rate and wearer demand the higher is the inhalation resistance and therefore the greater is the negative pressure. This is shown in Fig. 7b, where device CF 1 has a high inhalation peak even at the sinusoidal flow of 50 l/min derived from the test in the appropriate European Standard. This situation was recognized in BS 4275, where clause 7.3.2.2, Work rate, states 'For continuous flow air line equipment fitted with tight fitting face masks, the wearer cannot inhale at higher rates than the supply rate, the mask collapses on the wearer's face, gross inward leakage is permitted [may occur] and/or removal of the mask is forced'. With this proviso stated in the Standard, and with the analogy with PAR stated in Annex D.1.3, it is difficult to see the logic behind the allocation of an APF of 100.

It might be argued that the wearer of these devices can adjust the air supply flow rate to compensate for these high negative pressures. In some devices this can only be done by actually adjusting the pressure at the point of attachment to the works air supply regulator. Even when devices are fitted with belt worn air flow controllers (either a pressure control device or a continuous flow valve), it is unlikely that for short periods of intense work or unexpectedly high breathing rate that the wearer will adjust the air flow rate to compensate on each occasion. APFs cannot be set on these type of assumptions.

It is likely that devices CF 2 and CF 3, with minimum flow rates of 160 and 165 l/min, respectively, would be uncomfortable to wear for long periods with these high flow rates and relatively high exhalation resistance values. Provision of flow rates at these levels simply ensures that the device passes the Standard when it is tested at 30 and 50 l/min. Whether this is comfortable for the wearer is not assessed.

Self-contained positive pressure breathing apparatus

As shown in Table 2 and Fig. 4, the self-contained positive pressure BA (SCBA PP) maintains a positive pressure at all the test breathing machine rates. This is to be expected, given that there is a 100 l/min sinusoidal flow rate test within the European Standard for these devices. The positive pressure demand full face mask BA is allocated an APF of 2000, although the lack of workplace protection data for this type of apparatus means that the APF is unsupported. However, it is known that in laboratory inward leakage tests leakage levels can be very low, giving protection factors of the order of 20000 or greater provided that the face mask is a good fit on the wearer.

CONCLUSION

It is not the purpose of this paper to suggest that an 'equivalent' device with an apparently lower breathing resistance characteristic to that of the benchmark device should have its APF increased. The purpose of this work is to confirm or otherwise that the choice of benchmark and equivalent device is not unreasonable.

On the basis of the breathing resistance traces examined for all devices, working at their manufacturers' minimum design condition, then broadly speaking the principle of equivalence for most devices seems justified. It should be stressed that this does not justify the level at which the APF is set for the benchmark device or for their equivalents, but that decisions made about equivalences of other devices, based presumably on operational principles, are supported.

In the case of PARs and AFAH devices, it seems that when the breathing rate exceeds the air supply,

although some increase in the negative pressure occurs within the face mask, the extra air needed is supplied by the wearer's own effort, i.e. by lung power. This is not an ideal situation as it imposes additional physiological load, but, as previously stated, the wearer can self-regulate the workload.

For devices with demand valves, once the demand valve is opened by the wearer's breathing effort, the device supplies sufficient air according to need and thus maintains reasonable inhalation resistance.

Continuous flow compressed air line BA were the only devices tested which have a problem when operating at the manufacturers' minimum design condition, when subjected to increased non-sinusoidal breathing rates of 67 and 88 l/min minute volumes. This is predictable and it is difficult to see the justification for an allocation of an APF of 100 when the performance of this device is compared with that of some devices having APFs of 40.

Many of the devices assessed in these tests are used in hazardous atmospheres, confined spaces, atmospheres containing asbestos, chemical spillage situations, oxygen-deficient atmospheres, etc. Given that users rely on the values of APF as part of their selection procedures, it is stating the obvious, but nevertheless very true, that more workplace performance information, obtained by informed investigators using approved techniques, is badly needed.

Until sufficient workplace data exist on which to base APFs the users of RPE must continue to employ the current values of APFs in their selection process, except for the continuous flow compressed air breathing apparatus, for which an APF of 40 is recommended. However, as and when evidence is available to support or question the current equivalences, this should be considered by the appropriate Standards committees and amendments published where a change in the value is justified.

REFERENCES

British Standards Institution. (1997) BS4275: Guide to implementing an effective respiratory protective device programme. London: British Standards Institution.

Campbell DL. (1984) The theoretical effect of filter resistance and filter penetration on respirator protection factors. J Int Soc Respir Protect; 2: 198–204.

European Committee for Standardization. (1994a) European Standard EN 138: Respiratory protective devices—fresh air hose breathing apparatus for use with full face mask, half-mask or mouthpiece assembly—requirements, testing, marking. Brussels: European Committee for Standardization.

European Committee for Standardization. (1994b) European Standard EN 139: Respiratory protective devices—compressed air line breathing apparatus for use with full face mask, half-mask or mouthpiece assembly—requirements, testing, marking. Brussels: European Committee for Standardization.

European Committee for Standardization. (1998) European Standard EN 136: Respiratory protective devices—full face masks—requirements, testing, marking. Brussels: European Committee for Standardization.

European Committee for Standardization. (1999) European Standard EN 148-1: Respiratory protective devices—threads for facepieces—Part 1: Standard thread connection. Brussels: European Committee for Standardization.

Hack AL, Bradley OD, Trujillo A. (1980) Respirator protection factors: part II—Protection factors of supplied-air respirators. Am Ind Hyg Assoc J; 41: 376–81.

Johnston AR, Myers WR, Cotton CE, Birkner JS, Campbell CE. (1992) Review of respirator performance testing in the workplace: issues and concerns. Am Ind Hyg Assoc J; 53: 705–12.

Myers WR, Hornung RW. (1993) Evaluation of new in face-piece sampling procedures for full and half facepieces. Am Occup Hyg Assoc J; 37: 151–66.

Nelson TJ. (1995) The assigned protection factor of 10 for half-mask respirators. Am Ind Hyg Assoc J; 56: 717–24.

Nelson TJ. (1996) The assigned protection factor according to ANSI. Am Ind Hyg Assoc J; 57: 735–40.

Nelson TJ, Colton CE. (2000) The effect of inhalation resistance on facepiece leakage. Am Ind Hyg Assoc J; 61: 102–5.

Vaughan NP, Tierney AM, Brown RC. (1994) Penetration of 1.5–9.0 μm diameter monodisperse particles through leaks into respirators. Ann Occup Hyg; 38: 879–93.