The evaluation of fabrics in relation to their use as protective garments in nursing and surgery. II. Dispersal of skin organisms in a test chamber

By O. M. LIDWELL, C. A. MACKINTOSH and A. G. TOWERS

Central Public Health Laboratory, Colindale Avenue, London NW9 5HT

SUMMARY

The effectiveness of a representative range of fabrics in restricting dispersal through them of dry skin-borne bacteria has been examined. The fabrics were tested made up into trousers which were worn by volunteers during standardized exercise in a test chamber operated within a unidirectional flow clean-air room. Under these conditions, with careful attention to sealing at ankles and waist, it was possible to estimate penetration as low as 0·3 %. Penetrations as low as 1 % were observed with some synthetic fabrics. These had a relatively high surface resistivity and developed significant electrostatic charges.

When the observed values for penetration were compared with the results of a series of measurements and tests made on the fabrics it was clear that the correlation between these values and the other results was in every case very close for all the five woven cotton or cotton terylene fabrics but that no measurement or test was capable of predicting the behaviour of all the other materials in dispersal experiments. The inherent variability of dispersal experiments seems to be very great. With a standard deviation of the approximately log-normal distribution of the experimental values as high as about 2 times the mean, it is necessary to carry out as many as 20 replicate experiments in order to differentiate with certainty between garments with a two-fold difference in penetration.

INTRODUCTION

Physical measurements and bench tests have been carried out on a small representative series of fabrics (Lidwell & Mackintosh, 1978). In order to assess the value of any of these measurements or tests as indicators of the effectiveness of a fabric used for protective garments it is necessary to make comparisons with the performance in use of garments made from them. Such garments might be required for a variety of purposes and these will determine the character of a suitable test system, in particular water repellency might be of critical importance when the source of contamination or the sensitive site is wet. There is evidence that this may be the case in the nursing of large area burns for example (Hambraeus, 1973). In this paper we are concerned only with dispersal in dry situations.

A major source of particulate bacterial contamination of the environment is to be found in the dead skin scales shed by all persons. In another paper (Mackintosh

et al. 1978) we discuss some of the characteristics of these and the differences between individuals in the size, numbers and bacterial load of those dispersed. The shed scales are fragmented and irregularly shaped. They are essentially plate-like in character with a median minimum projected diameter of about 30 μm and a thickness of about 2–5 μm. They carry the normal skin flora of the individual but may also act as vehicles for micro-organisms from other sources. These may arise from other carrier sites on the body, and this is the principal means of dispersal of *Staphylococcus aureus* from carriers of this organism, or by contamination from extraneous sources. A protective garment may be required to prevent contamination of the clothes worn beneath it or to prevent dispersal of strains carried on underlying clothing or skin, whether these arise from true carriage or from previous contamination.

MATERIALS AND METHODS

For test purposes it is easiest to make use of naturally carried organisms. There is no reason to think that penetration through the fabrics will differ with the origin of the organisms on the contaminated scales. There are numerous published accounts of the effectiveness of a variety of garments (mostly designed with a view to use in the operating room) tested by standardized exercise in some sort of a test chamber (e.g. Duguid & Wallace, 1948; Bernard *et al.* 1965; Blowers & McClusky, 1965; Whyte *et al.* 1976). These rarely showed reductions in dispersal of more than 90% but, being tests of whole garments, there were usually possibilities for dispersal of organisms in other ways than through the fabrics themselves. Some parts of the body may have been left uncovered; sealing around wrists, ankles, throat or waist may not have been completely effective; extraneous contamination may have raised the background level so that it was a significant fraction of the observed dispersal. Since some of the bench tests previously described showed differences as great as 10^5 it seemed essential to use a test system capable of evaluating the penetration of particles through the fabrics down to levels well below 10%.

The test system

We were only concerned in this study with the performance of the fabrics, and wished to avoid problems arising from deficiencies in garment design. It appeared, therefore, that the most convenient system would be to examine dispersal from below the waist, when it would only be necessary to fabricate or obtain trousers of each material. Little variation in garment size would then be necessary. The trousers were elasticated at the waist and ankles to give a close fit but full reliance was not placed on this alone to ensure an air-tight closure.

Chamber A (Series A)

This was 2·5 m high × 0·9 m × 0·9 m, lined with aluminium, with a vinyl tiled floor. One side of the chamber was clamped by bolts against a sealing gasket and could be removed for access. The upper part of the subject's body was enclosed

in a ventilated hood formed from a length of polyethylene tube 0·6 m in diameter suspended from a D-shaped plate. The lower edge of the hood was tied around the waist below the upper edge of the trousers. Air was extracted from the hood through a pipe inserted into the plate. Replacement air was drawn in from outside the chamber through a cotton wool plug in a second tube. The restriction to inflow resulted in a small reduction in pressure so that contamination released from the upper part of the body did not escape into the chamber. A wire frame prevented collapse of the hood under suction.

The air of the chamber could be cleaned by recirculation through a high efficiency filter at a rate of 2·8 m³/min. During the experiments air was sampled from the chamber at 160 l/min and make-up air entered the chamber through a filter (90 % efficiency at 5 μm against test dust No. 2, British Standard 2831). The air in the chamber was mixed continuously by a small desk fan placed on the floor directed upwards.

The test procedure was as follows: the subject entered the antechamber and undressed down to blouse or shirt, underclothes and socks (removing tights or stockings) and put on a pair of disposable gloves. He or she then stepped onto a disinfected plastic mat and fastened a pair of disinfected plastic bags over the feet using rubber bands. The trousers (sterilized) to be tested were then put on, with the elasticated legs over the plastic bags, the hood ventilation was started and the subject entered the chamber. The lower edge of the hood was fastened around the waist and the chamber door closed.

Then: (1) The recirculation system was run for 2 min with the subject at rest. (2) The subject remained at rest for 2 min while an air sample was taken. (3) The subject marched on the spot for 2 min at 84 steps/min. (4) An air sample was taken for 5 min with the subject at rest. (5) A further sample was taken for 2 min with subject still at rest. When preliminary experiments had shown that step 4 sampled essentially all the available airborne organisms step 5 was discontinued and a 1 min sample was taken during the first minute of step 3. Control runs without protective trousers were usually carried out by removing the trousers after step 4 or 5 and repeating from step 1.

The floor of the chamber was washed with 1% aqueous Hycolin after each experiment and the walls and other surfaces at regular intervals. The hood and plastic bags were disinfected with 70% ethyl alcohol. The trousers were autoclaved except for those of Tyvek which would not stand this treatment and were only brushed down. All air samples were taken by a slit sampler (Bourdillon, Lidwell & Thomas, 1941) onto nutrient agar plates and incubated overnight at 37 °C before counting the colonies grown.

Records were kept of the relative humidity and temperature.

Chamber B (Series B)

The results of the experiments in chamber A showed that these procedures were inadequate to reduce the degree of contamination sufficiently and a much more satisfactory system was designed and constructed (Fig. 1). The whole procedure was carried out inside a uni-directional flow room supplied with filtered air over
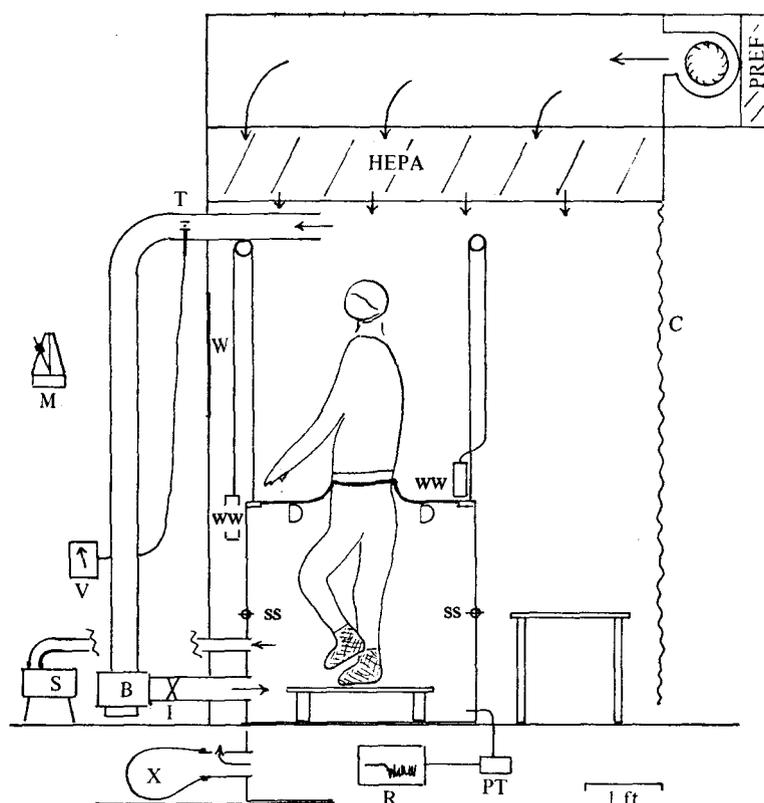
Fig. 1. Test chamber, series B. PREF and HEPA, Pre- and high-efficiency particle filters supplying clean air to the chamber; B, centrifugal blower discharging clean air into the box; C, plastic curtain containing the uni-directional downward flow of clean air in the chamber and defining a space for putting on the sterile trousers under test; DD, Neoprene foam sheet diaphragm forming an air-tight seal around the waist below the top of the trousers; I, iris diaphragm controlling the rate of clean air supply to the box; M, metronome for maintaining a steady and reproducible rate of stepping; P, platform to give a suitable waist height; PT, pressure transducer feeding into R, amplifier and recorder; S, air sampler for collecting bacteria or skin scales dispersed into the box; ss, rubber gasket seal between the two halves of the box; T, thermistor air speed detector monitoring the rate of clean air supply to the box; V, indicator showing the air speed in the clean air supply duct; W, window in wall of chamber; ww, counter-weights for easy lifting of the top half of the box and for compressing the seals when this is lowered onto the bottom part; X, blow-off for excess air with plastic bag to reduce pressure oscillations in the box when exercising.

the ceiling area giving a uniform downflow velocity of about 0·4 m/sec. The subject, after undressing in an antechamber, put on disposable gloves, a disinfected cap and a sterile T-shirt and entered the experimental room. Standing on a disinfected plastic mat he or she put plastic bags, secured with rubber bands, over the feet and put on the trousers to be tested. The legs of the trousers were then drawn over the plastic bags and a disinfected pair of neoprene foam bootees (wet-suit boots) pulled over the bags and trouser ends so as to form as neat and tight a seal as possible around the ankles. The top half of the box was then raised

and the subject stepped inside, pulled down the upper half, drawing the hole in the foamed neoprene gasket over the head and shoulders. In order to get a good seal around the waist over the top of the trousers a platform of suitable height for the individual concerned was placed in the box. The top half of the box was held firmly down onto the bottom half by placing the counterweights onto the four corners.

The box could be flushed with clean air drawn from below the inlet filters, at a rate of about 3m³/min. When sampling this was reduced to about 350 l/min which was sufficient to replace the sampled air (160 or 24 l/min) and to maintain a positive pressure inside the box even when the subject was exercising. The variations in pressure during exercise were reduced by the large plastic bag placed over the exhaust port from the box with only a 2·5 cm diameter hole left for the escaping air. The air supply to the box was monitored by a thermistor type flowmeter in the trunking and the pressure by a rapid response pressure trans-ducer (Schaevitz PTD-3G) coupled to a recorder. At the reduced air supply rate, with the sampler taking 160 l/min, the pressure inside the box averaged 0·9 mm water gauge, whether the subject was still or exercising, although with the latter condition it might drop to near zero at times. With the sampling rate also reduced the pressure difference rose to about 5 mm water gauge.

When sampling under control conditions, wearing underclothes only, the sampling rate could be reduced to 24 l/min in order to avoid overcrowding of the plates when the rate of dispersal was high.

Experimental procedure: (1) The box was flushed at 3000 l/min for 4 min with the subject at rest. (2) The subject remained at rest and a 4 min sample was taken with the air supply reduced to 350 l/min. (3) A 4 min sample was taken, with the same rate of air supply. The subject exercised for the first $2\frac{1}{2}$ min at 84 steps/min. (4) The subject left the box and the air flow was increased to 3000 l/min. (5) The subject removed the trousers and then re-entered the box. Steps 2 and 3 were then repeated. At the end of each experiment the box and platform, the stool and the floor of the experimental room were washed with 1% aqueous Hycolin. The mat, boots, caps and plastic bags were swabbed with 70% ethyl alcohol. The trousers and T-shirts were wrapped for sterilization. The Tyvek trousers were sterilized by ethylene oxide or by low pressure steam and formaldehyde. *The sample plates, nutrient agar, were incubated overnight at* 37 °C *before counting.*

The trousers, as has been described above, were normally autoclaved between each experiment. They were not laundered. The effects of laundering on the properties of a fabric may, in practice, be very important, but in this series of experiments, intended primarily to establish a correlation with the various measurements and bench tests, they were not of immediate concern.

Selection of subjects

The sensitivity of the test system depends on the numbers dispersed during the exercise period relative to the background value. By making use of subjects dispersing the largest numbers of skin scales carrying micro-organisms the

detectable ratio between dispersal when wearing trousers and that produced in underclothes only would be reduced to the lowest possible. However, such subjects might differ from the average in other ways also and these differences might affect penetration, e.g. if the scales shed had a different size distribution. It was therefore decided to use a panel of volunteers including both males and females.

In series A ten subjects, five men and five women, were examined. One of the female subjects was found to disperse so few organisms as to contribute no information to this study. The remaining nine subjects carried out one dispersal experiment with each of the ten fabrics and one duplicate (a different fabric for each subject). They each also carried out nine dispersal experiments in underclothes only.

In series B six subjects were used, three male and three female, five of whom had taken part in series A. Each subject carried out two experimental runs, each of which included dispersal in trousers and in underclothes, on six of the fabrics, plus one run using Balloon cotton trousers and one run in trousers made of polyvinyl chloride sheeting.

RESULTS

Duration of exercise

In the design of dispersal experiments the question that immediately arises is that of the length of time the garment should be worn and the duration of any standardized exercise necessary to obtain representative results. Is it necessary for the fabric to become in some sense saturated with the particles dispersed from the body before penetration and dispersal into the environment takes place at a steady rate? The use of a slit sampler for the air sampling enabled a time study to be made of the rate of dispersion. A selection of results for the first minute of exercise is shown in Fig. 2 for several fabrics. It was clear that there were no significant differences in the way in which dispersal built up from the start of the exercise period. There was, however, some tendency for dispersal to build up more rapidly when trousers were worn. This might derive from a greater tendency for skin scales to be dislodged during the quiet period as a result of friction between skin and garment during this time. There was, however, no indication whatsoever of any lag in dispersal due to absorption or other properties of the fabrics worn.

This was also confirmed by the results of a limited number of long duration studies when a volunteer exercised for up to 30 min. After a few minutes the contamination level in the chamber reached a plateau which persisted with irregular fluctuations as long as the experiment continued. The relatively short exercise periods used seem therefore to be not only convenient but likely to give a reasonable representation of the performance of the fabrics in use.

The sampling system inevitably collected only a fraction of the particles dispersed. Some settled on the floor of the chamber, some were lost in the air which flowed out as a means of preventing the ingress of extraneous contamination and some remained in the chamber air at the end of the sampling period. From the air flow volumes given, and assuming losses by sedimentation at 30 cm/min
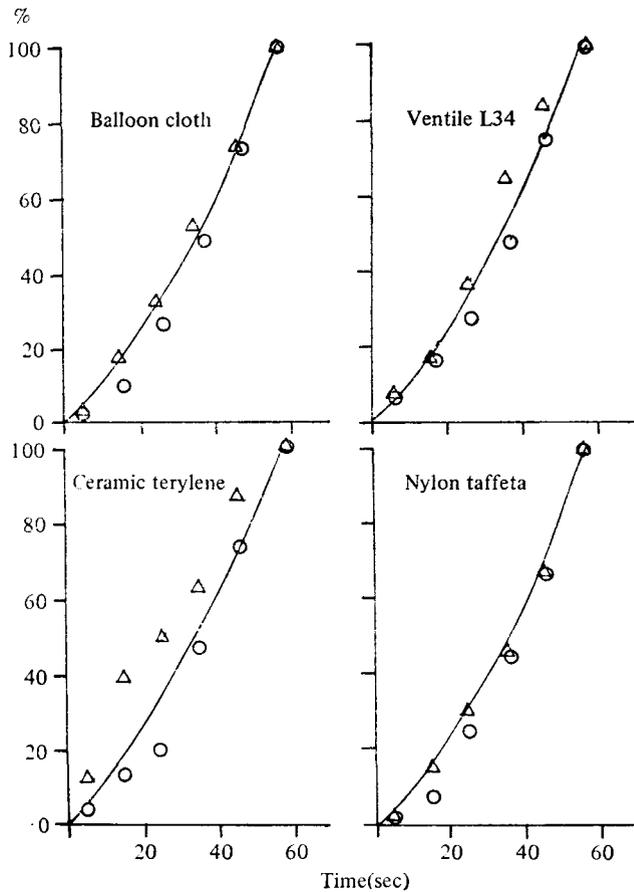
Fig. 2. Build up of air borne contamination over the first minute of exercise. The circles are data from subjects in underclothes, the triangles from subjects wearing trousers of the material indicated. The values are cumulative percentages of the total reached by the end of the first minute.

onto the chamber floor, it is easy to calculate the fraction collected. For the first series of experiments, A, this was approximately 0·19 and for the second, B, 0·24. These values correspond, in the first series, to about 40% and, in the second series, to about 60% of the numbers dispersed during 1 min of the standardized exercise.

Dispersal

The results of both series of experiments are shown in Tables 1 and 2 and in Fig. 3. There was a great variability in dispersal from the different subjects, from the same subject on different occasions and in the penetration of particles through trousers of the same fabric, both in respect of tests carried out by different individuals and in respect of duplicate tests by the same individual. Since the numbers dispersed by a given individual on different occasions appeared to be distributed log-normally all the analyses were carried out using the logarithms of the numbers recovered in the samples.

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Table 1. *Geometric mean numbers of bacteria carrying particles recovered in dispersal experiments*

	Series A	Series B
Control (chamber empty)	13 (2·33)	3·3 (2·64)
At rest in trousers	27 (1·34)	2·8 (2·43)
At rest in underclothes	30 (1·38)	5·5 (3·04)
Exercise in PVC trousers	—	2·3 (2·16)
Exercise in other trousers	— (3·00)	— (3·03)

Exercise in underclothes:

	Series A	Series B
Males:		
OML	—	16750
CAM	637	855
RRM	1607	565
TP	547	—
GM	258	—
BC	121	—
Females:	(1·83)	(2·37)
AGT	480	266
JR	195	681
IF	184	—
JCM	104	148
GH	23	—
Mean for all subjects excluding GH	288	774

The figures in parentheses give the geometric standard deviations, i.e. the ratios of the 84th percentiles to the means.

The control values given for Series A, the three uppermost numbers, are the experimental values multiplied by 2·5, in order to make them comparable to the dispersal figures. The control sampling time in Series A was only 2 min while the dispersal sampling time was 5 min.

Table 2. *Percentage penetration through trousers of various fabrics*

Code	Fabric	Series A (a)	Series A (b)	Series B (a)	Series B (b)	Both series together
U	Utopia plus	76	74	—	—	74
B	Balloon cotton	54	49	34	34	41
F	Featherproof cotton	35	29	—	—	29
P	Pima cotton (Quarpel proofed)	19	11	—	—	11
V	Ventile cotton, L34	14	6	9·7	9·4	7·5
J1	Dexter (non-woven)	25	18	8·4	8·2	12·1
J2	450 (non-woven)	30	24	6·7	6·4	12·4
T	Tyvek (non-woven)	20	(12)	3·6	3·3	3·3
NT	Nylon Taffeta	11	(2·4)	1·4	1·1	1·1
C	Ceramic terylene	12	(3·5)	1·3	1·0	1·0
PVC	Polyvinyl chloride sheet	—	—	0·3	(0·0)	< 0·3

Columns (a) give the direct ratios to dispersal in underclothes only, columns (b) the figures corrected for background.

For series A this has been taken as that at rest, mean of the values in trousers and in underclothes; for series B the value for exercise in PVC trousers has been used. The figures in parentheses are those considered unreliable, see text.
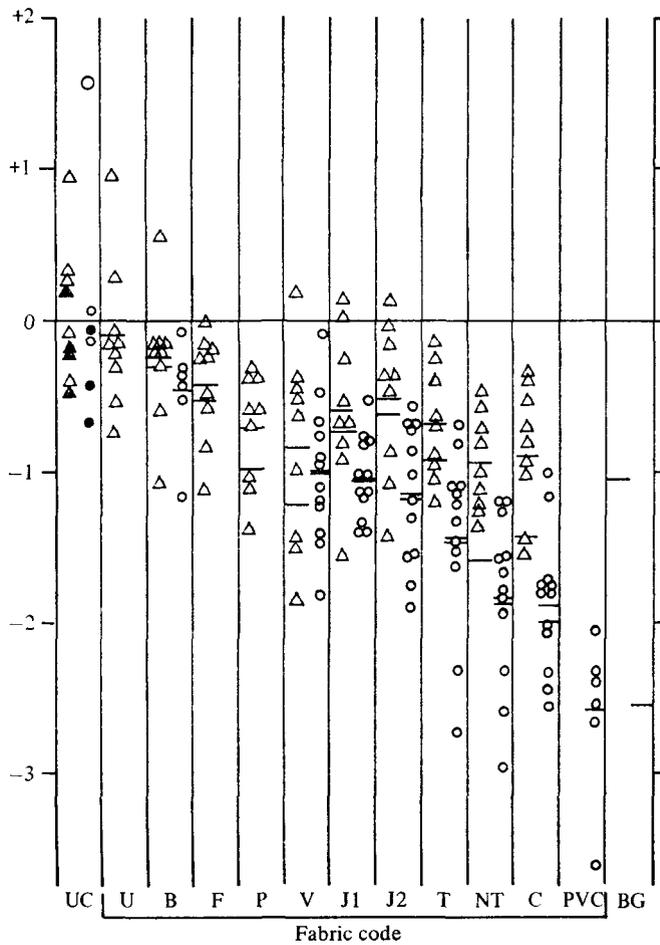
Fig. 3. Reduction in dispersal when wearing trousers of the given fabric. The vertical scale gives, except for the left hand column, the logarithmic difference (base 10) between dispersal when exercising in underclothes and when wearing trousers of the fabric indicated. The left hand column, UC, shows the mean dispersal from the individual unclothed volunteers relative to the mean for all volunteers in each series. Values for series A are shown as triangles and for series B as circles. In the left hand column open symbols refer to male volunteers and filled symbols to the females. The horizontal bars show the mean values. Where there are two bars the lower is that corrected for the level of background contamination the mean values of which are shown in the right hand column, BG.

The reductions in dispersal when wearing trousers, as shown in Fig. 3, were obtained for series A by taking the difference between the logarithm of the numbers recovered in the test, with trousers on, and the logarithmic mean of the numbers recovered from the same subject in the nine dispersal experiments wearing only underclothes. For series B, where there was always a paired set of figures for dispersal with trousers and in underclothes only, the difference between the logarithms of these two figures was taken. As can be seen from the values given in Table 1 the use of paired figures did not reduce the variability of the

estimates of the reduction in dispersal when wearing trousers, which was much greater even than the variability of dispersal by the same individual on different occasions.

The standard deviation of the estimates, uncorrected for background, were 0·48 for both series (using logarithms to the base 10). Since the numbers of estimates were 19 and 12 in the two series respectively the standard errors of the estimates were about 0·15 and 0·14. The standard deviation of the difference between two estimates is therefore about 0·2 which corresponds to a difference of 0·4 (or 2·5 times) for a 95 % probability that the difference is real. If the two series are combined this will be reduced to about 2 times.

The estimates for penetration can be corrected, as in Table 2, for the influence of background contamination. This cannot be done by simply subtracting the mean background level from the numbers recovered in an individual experiment since the degree of variability in both figures is such that the numbers recovered in an individual dispersal experiment are sometimes less than the mean background. To circumvent this difficulty the logarithmic means of the numbers recovered in the dispersal experiments, with trousers and in underclothes only, have been converted into arithmetic form and the mean background subtracted from each. The corrected estimates for the reduction in dispersal when wearing trousers have then been derived from the ratio of the two resulting values. When the background is as high as half or more of the mean numbers recovered in the dispersal experiments the correction becomes excessive and the corrected values very unreliable.

In series A the background level was about 10 % of the mean unclothed dispersal so that apparent reductions to less than 20 %, when corrected, fall below 10 % and must be considered unreliable. This was so for the experiments with trousers of Nylon Taffeta and Ceramic terylene. In addition, the results for the experiments with Tyvek come close to this level and since these trousers could not be autoclaved and were only cleaned by brushing down between each experiment the results with this fabric in series A are also suspect.

In series B the changes in procedure led to a ten-fold reduction in background levels compared with series A. These were no more than 0·4% of the mean unclothed dispersal. The background levels recorded in this series actually fell in the sequence, pre-experiment control (empty chamber), at rest in trousers, exercise in PVC trousers. This was probably due to progressive clean up by the flushing air after the disturbances associated with setting up the experiment. The results with the impermeable PVC trousers confirmed the effectiveness of the precautions taken for sealing at ankles and waist and the mean value from these experiments, no more than 0·3 % of the unclothed dispersal figures, was used to obtain the corrected penetration figures shown in Table 2. The Tyvek trousers were disinfected in an ethylene oxide sterilizer or by low pressure steam and formaldehyde between each experiment in this series. The sensitivity in this series was such that estimates of penetration down to 0·3 % were practicable. In fact no fabric gave values below 1 % (except the PVC sheeting). The penetration values derived for both series together (last column in Table 2) have been obtained
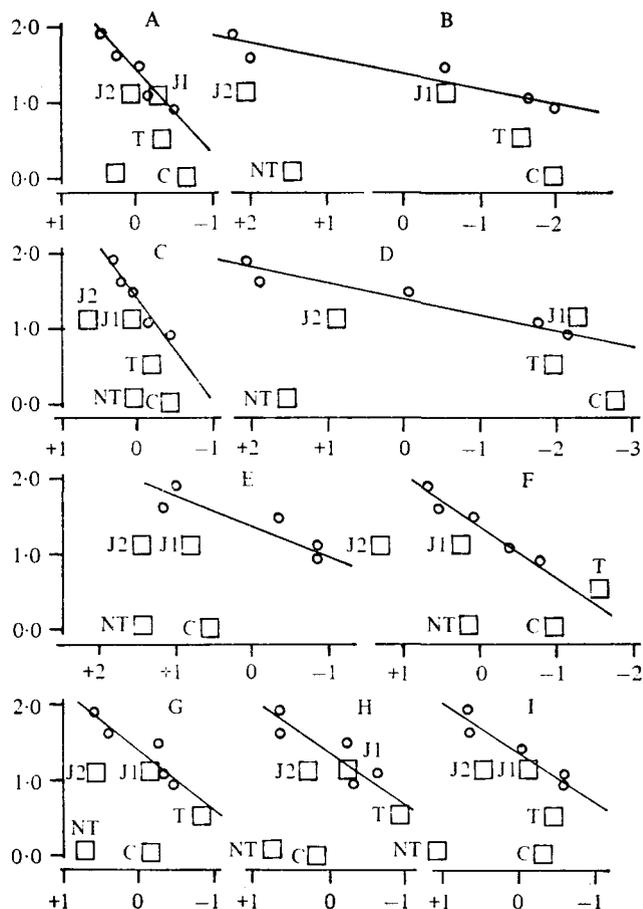
Fig. 4. Percentage penetration through fabrics worn as trousers in relation to various measurements and bench test results with the fabrics. The vertical scale, logarithmic base 10, gives the percentage penetration, the horizontal scale the measurement or bench test result as the logarithmic difference, base 10, between the test value and the mean value for that test for the five woven cotton or cotton–terylene fabrics. The values for these five fabrics, codes U, B, F, P and V, are shown as circles and the straight lines in the figure are the regression lines through these five points. The values for the other fabrics are shown as squares labelled with the code reference for the fabric concerned, i.e. J1, J2, NT, C and T. A, Measured pore diameter; B, microsphere rub-through; C, BS bubble diameter; D, talc powder rub-through; E, number of pores per cm^2; F, air flow; G, airborne dust $> 0.5\,\mu$m; H, airborne fluorescent particles; I, airborne talc powder.

as the geometric mean of the values derived from the series A and the series B experiments where both estimates were considered reliable.

Remembering that the high variability inherent in the experimental data implies that only differences in excess of two-fold can be regarded as statistically significant, the fabrics tested fall into four groups. Utopia plus, Balloon cotton and the Featherproof cotton all show considerable penetration, around 50 %. The close woven cottons, Pima and Ventile, together with the Johnson & Johnson

Table 3. *Observed penetration through fabrics worn as trousers relative to that predicted by reference to woven cotton fabrics*

Measurement or test

Material	Code	Pores/cm²	Largest pore	Bubble diam.	Airflow rate	Airborne penetration			Rub through	
						Royco	Fluorescent particles	Talc	Spheres	Talc
Nylon Taffeta	NT	1·9	1·6	1·3	1·4	1·9*	1·8*	2·0	1·6	1·6
450 (non-woven)	J2	0·9	0·4	1·2	1·2	0·7	0·5	0·6	0·7	0·5
Dexter (non-woven)	J1	0·6	0·0	0·2	0·4	0·2	0·1	0·2	0·2	−0·2
Tyvek (non-woven)	T	?	0·5	0·6	−0·2	0·2	0·2	0·6	0·5	0·4
Ceramic Terylene	C	1·6	0·7	0·8	0·7	1·2	1·5	1·2	1·0	0·8
Five cotton and cotton–terylene woven fabrics	U, B, F, P, V									
Correlation coeff.		0·896	0·952	0·974	0·981	0·887	0·858	0·952	0·939	0·967
Regression slope		2·4	0·9	0·7	1·5	1·2	1·4	1·5	4·9	4·8

The two bottom rows of the table give the correlation coefficients and the regression slopes between the observed values for penetration and the measurement or test results for the five cotton or cotton–terylene mixture woven fabrics. These values correspond to the straight lines shown in Fig. 4.

The values in the upper six rows show the difference between the observed penetration for a fabric and the value predicted from the observed measurement or test result by comparison with the results for the five fabrics, i.e. the vertical displacement of the point indicated in Fig. 4 by a labelled square from the regression line. All the results have been expressed logarithmically, base 10, and the table shows the predicted values minus those observed.

* These tests were carried out with the white nylon fabric (NB).

non-woven fabrics form the second group with penetrations of around 10%, Tyvek is appreciably better than these, with a penetration of only about 3% and the two woven, wholly synthetic fabrics, Nylon taffeta and Ceramic terylene- show penetrations as low as 1%.

Comparison with measurements and bench tests

In Fig. 4 the estimated penetration through the different fabrics is shown against the values obtained for the same fabric in the several tests. All the values are plotted on logarithmic scales and the test values are given as the difference from the mean value for the five woven cotton and cotton–terylene fabrics. It is apparent that there is a very good correlation between the penetration of skin carried micro-organisms through the fabrics and all the test measurements for these five fabrics, U, B, F, P and V, which are all similar in composition and structure. The straight lines drawn in the figure show the relationships for these fabrics and have been computed from the square root of the ratio of the two variances, defining the slope, to pass through the means of both quantities (orthogonal regression). Although the correlation coefficients for these five fabrics is very high with respect to all the test measurements, the slopes of the regression lines often differ greatly from unity (Table 3). This is particularly so for the rub-through tests, where the slope is nearly 5, i.e. penetration is proportional to (rub through)$^{0.2}$. A possible explanation might be that the heavy loading of particles in these tests results in blocking of the pores of the more closely woven fabrics by the larger particles so that penetration by the smaller particles is inhibited. Penetration in the dispersal tests also varied much less than proportionately to the number of pores per unit area of fabric, approximately penetration is proportional to (no. of pores/cm^2)$^{0.4}$.

The slopes with respect to the other test values lay between 0.7 and 1.5.

When we consider the other fabrics we see that, with the exception of the Dexter non-woven material, J1, which is always close to the regression lines for the five fabrics, the penetration values often differ widely from those which would be predicted from the results of the measurements or bench tests on the five fabrics. Table 3 shows the divergences in log$_{10}$ units, a positive value indicating less penetration than expected.

Considering the fabrics severally: the 450 non-woven material, J2, always shows lower penetrations than expected. The range of log difference lies between 0.4 and 1.2, i.e. between 2.5 and 15 times less penetration. Tyvek shows a smaller difference, generally in the same direction, up to about 4 times less penetration than expected.

The biggest differences, however, are shown by the all-synthetic woven fabrics of nylon and terylene. Although the Nylon Taffeta had an extremely open weave and by all tests and measurements should have shown a very high penetration, the penetrations observed in the dispersal tests were in fact little over 1%, the difference from prediction lying between 30 and 100 times.

Ceramic terylene is a close woven fabric and all the tests predict a low penetra-
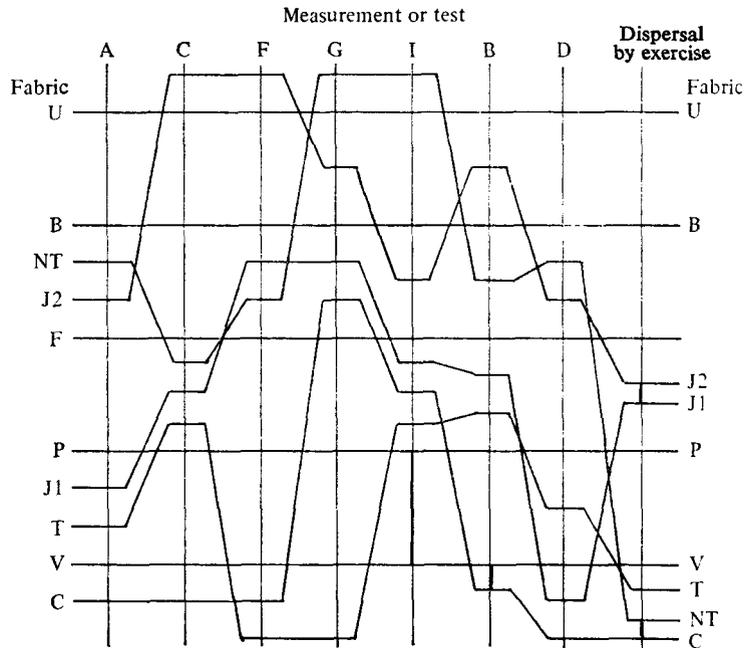
Fig. 5. Rank order of fabrics by measurement or tests. Rank orders are shown vertically with the highest measurement at the top. Thick vertical lines link values so close as to be indistinguishable. The measurement or test appropriate to each column is indicated by the same reference letter as in Fig. 4.

tion. The penetration observed is, however, between 5 and 30 times less than that predicted.

The changes in rank order of the fabrics according to the various tests and measurements are illustrated in Fig. 5. Since the five fabrics used as a reference set in Fig. 4 remain in the same rank order for all the tests they are shown in the diagram as horizontal lines. The total discrepancy between measurements or bench tests and dispersal through the Nylon Taffeta is obvious, as is the reduced rub-through by talc as compared with micro-spheres shown by the non-woven fabrics J1 and J2.

DISCUSSION

It is clear that none of the physical measurements or bench tests carried out on the fabrics was capable of predicting the behaviour of all the fabrics in dispersal tests.

The two synthetic woven fabrics, nylon and terylene, always reduced dispersal to much lower levels than would have been expected from the test results. Both these fabrics have high electrical resistance and can develop substantial electrostatic charges. Tests by the Shirley Institute (Didsbury, Manchester, England) showed surface resistivities exceeding 10^{12} Ω/square and residual charges on pieces 5×12.7 cm, after contact with similar material, between 18 and 73 nC. These values for surface resistivity are about 100 times greater than the upper limit for fabrics for use in hospitals recommended in Hospital Technical

Memorandum No. 1 (1968). They are, however, significantly lower than the values associated with fabrics woven from untreated yarns of these materials. The reduction may be as much as 10–100 times. The fabrics in question exhibited none of the extreme features associated with untreated synthetic fabrics such as clinging to the skin, attraction or repulsion for small objects or hair, or even crackling and visible sparking. Presumably they had received some anti-static treatment in manufacture. This was confirmed by the effects of laundering which resulted in an increase in the surface resistivity to above 10^{13} Ω/square.

If desquamated skin scales are charged (Lees & Brighton, 1972) this would accentuate the effects of charges on the fabric in restricting penetration. It would be of practical interest to see whether it was possible to produce or treat fabrics of synthetic yarns so that the electrostatic charges developed on wearing were sufficient to reduce the penetration by particulate material significantly without the risk of undesirable static effects. No charges sufficient to affect the test results appear to have been developed in these fabrics by any of the bench test methods.

The other synthetic material tested, Tyvek, only showed moderate divergence from expectation. In relation to most tests this could have resulted from the very small number of holes. The actual number was very difficult to determine, but this would not have been expected to have affected comparison with rub-through tests.

The non-woven fabric 450 reduced dispersal significantly more than would have been deduced from any of the measurements or bench tests. This material is in the form of a fibrous mat. As a result it has a very low resistance to air flow and the channels through the material are mostly very tortuous. Plate-like particles, such as skin-scales or talc, pass through such a material less readily than smooth, near-spherical objects. When worn as a garment the large area of material, with a very low resistance, will result in very low air velocities in the channels through the fabric. Whether this might result in a reduced penetration by airborne particles is not clear but would clearly do so in the limit as the air velocities approached zero.

It is not easy to say which test or tests are the most valuable for the preliminary assessment of a fabric for use in protective clothing. The size of the largest pores which penetrate the fabric is a simple measure which needs little equipment to estimate and which gives as good a guide as any. There are, however, difficulties in obtaining a reliable value for some fabrics and these have been discussed in the previous paper (Lidwell & Mackintosh, 1978).

The BSI method using the bubble pressure is easy to carry out but encounters difficulties with some kinds of proofing and may give totally erroneous results with a non-woven fibrous mat (as the 450 material).

The rub-through methods tend to give a very sharp differentiation between the relatively penetrable and the relatively impermeable materials. The transition region is presumably dependent on the particle size distribution of the test particles. A suitable grade of talc powder provides a test particle very similar in many respects to desquamated skin scales. The test is easy to set up and the equipment compact.

Penetration by airborne particulates is, after pore size, the most directly related to dispersal. The experimental set-up is the most complex of all those studied and there does not seem to be any substantial gain in predictive capability although the actual numerical values are the most directly related to the penetrations observed in the dispersal experiments. Rather unexpectedly the figures for airborne penetration by very small particles, e.g. the tests using a particle counter on naturally occurring airborne particles when most of those counted were between 0·5 and 1 μm, showed as good a correlation with the dispersal tests as those for penetration by particles of comparable size to the skin scales, e.g. talc powder.

The protective value of fabrics in wet situations, e.g. the nursing of extensive burns, has been examined by Hambraeus and her colleagues (Hambraeus & Ransjö, 1977) who found only limited protection from those studied. It seems unlikely that any fabric with the porosity and handle necessary for a comfortable garment could ever be totally resistant to penetration by watery fluids when rubbed, although the attainable degree of water repellency might be adequate in less demanding situations. The use of plastic aprons (Lidwell et al. 1974) over garments resistant to dry particle penetration seems to be the most likely practical solution.

A striking feature of the dispersal tests, which is also apparent in other published data, is the extremely high variability in the values obtained. This complicates the assessment of any fabric by demanding a large number of replicate experiments. Something like 20 appear to be necessary in order to achieve discrimination between fabrics at the $2\times$ level. Not only do individuals differ by a very large factor in their *mean* rate of dispersal (the ratio between the highest and the lowest among the 11 subjects tested here was about 1000 : 1), but individuals also vary greatly in their dispersal on different occasions, even on the same day.

The logarithmic standard deviation for an individual was about 0·3 (logarithms to base 10), so that the range of values observed for each individual exceeded 10 : 1. Some aspects of the dispersal of micro-organisms on skin scales are discussed in another paper (Mackintosh et al. 1978).

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