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The control by ventilation of airborne bacterial transfer between hospital patients, and its assessment by means of a particle tracer

III. Studies with an airborne-particle tracer in an isolation ward for burned patients

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SUMMARY

Airborne-particle transfer has been studied in a burns unit using potassium iodide particles. The observed rates of transfer were in good agreement with the values predicted by a theoretical model.

An estimate of the average transfer between rooms under conditions of normal activity and with correctly functioning ventilation showed that the isolation system was highly efficient, the proportion transferred being probably less than 1 in 10^5. However, the ventilation often did not function as designed and under these conditions the efficiency was reduced by a maximum of a factor of ten. These rates of transfer do not seem great enough to account for the high rate of cross-infection found in this unit.

INTRODUCTION

Much effort has been expended in recent years in devising ventilation systems to reduce the airborne spread of bacteria in hospital wards, but methods for evaluating the efficiency of these are not altogether satisfactory and have only occasionally been attempted. In a preceding paper (Foord & Lidwell, 1972) a method has been described for studying airborne particle transfer between parts of a ward by use of potassium iodide particles. We now present the results of a series of experiments using this method in an isolation ward for burned patients at Akademiska sjukhuset, Uppsala. In spite of a complete ventilation system, including airlocks, earlier studies have revealed a considerable amount of cross-infection between patients in the ward (A. Hambraeus, to be published). The purpose of the investigation was to determine the effectiveness of the ventilation system and hence the role of airborne bacteria as a possible cause of cross-infection. Comparison could also be made with the theoretical analysis of isolation system elaborated in the second paper of this series (Lidwell, 1972).

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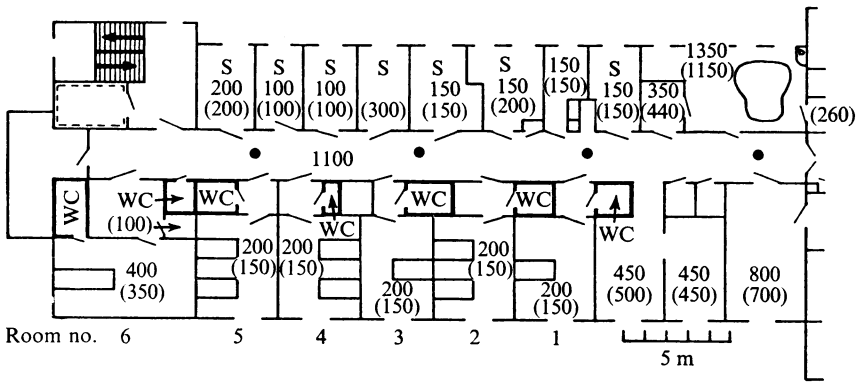


Fig. 1. Plan of the ward. Input ventilation is shown for each space as m.³/hr., extract volumes are given in parentheses, an additional 100 m.³/hr. was extracted from each of the patient room W.C.'s, except no. 6. The sampling sites, when room 1 was the source room, are indicated by ●; S = service room.

MATERIALS AND METHODS

Ward design and ventilation

Fig. 1 shows the plan of the isolation ward. It is entered via an airlock with double doors and a passage runs down the middle of the ward. There are five patients' rooms of similar dimensions and a sixth larger room containing an air bed. All of these have individual airlocks and they are situated along one side of the passage. On the opposite side of the passage are service rooms and the bathroom. The bathroom has three doorways; one of these opens directly to the passage for bed transport, and the other two open via airlocks; one into the passage (I) and the other into the ward airlock (II). The designed ventilation input and extract are shown in each part of the ward (the extract is in brackets). The net result is a near-balanced ventilation with little or no other air flow between the ward and the exterior.

Fig. 2 shows the air flow as designed for a typical patient room. The air input to the room is 200 m.³/hr. (which approximately equals 4 air changes/hr.). Of this input, 150 m.³/hr. is extracted directly from the room, the remaining 50 m.³/hr. passes into the airlock. A further 50 m.³/hr. is drawn from the passage into the airlock making up the total extract from the W.C. of 100 m.³/hr.

The ventilation of the bathroom is shown in Fig. 3. The designed input is 1350 m.³/hr. and the extract is 1150 m.³/hr. Airlock I has an input of 350 m.³/hr. and an extract of 440 m.³/hr., this results in a net deficit in airlock I of 90 m.³/hr. which is supplied as 45 m.³/hr. from both the bathroom and the passage. The extract from airlock II is 260 m.³/hr., this is provided as 130 m.³/hr. from both the bathroom and the ward airlock. This leaves a net surplus of air supply in the bathroom of (200–175) m.³/hr. = 25 m.³/hr. which escapes into the passage beneath the direct door.

Titanium tetrachloride smoke was used to determine the direction of air flow beneath the doors.

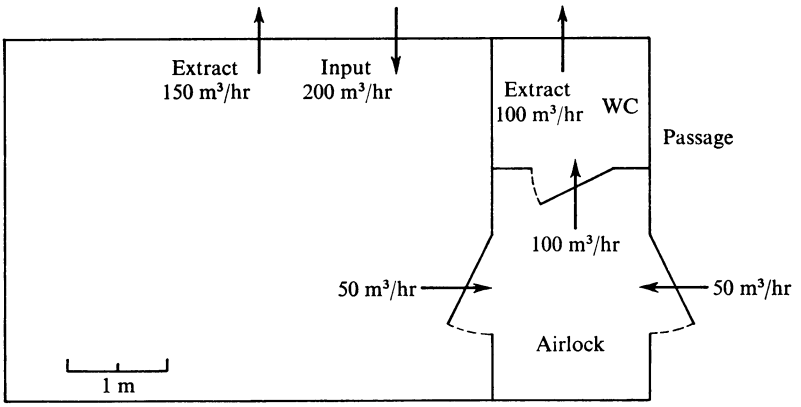


Fig. 2. Diagram showing the design ventilation of patient rooms 1–5.

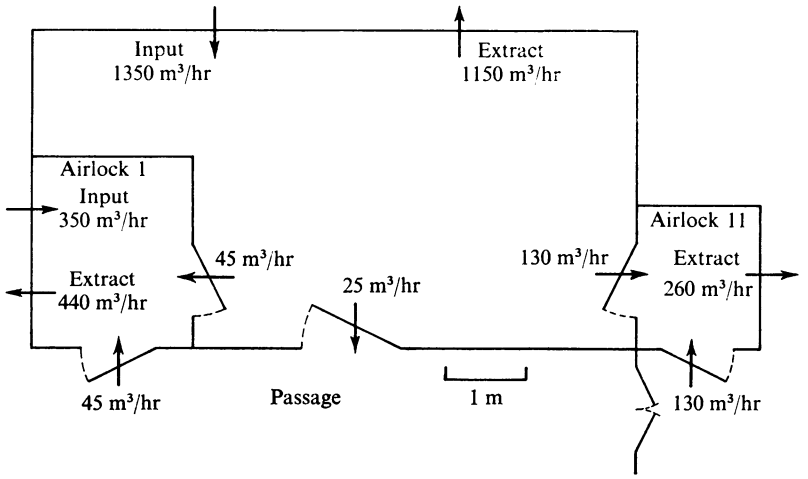
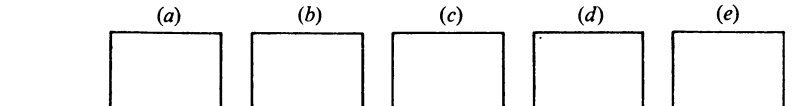


Fig. 3. Diagram showing the design ventilation of the bathroom.



Room no.	(a)	(b)	(c)	(d)	(e)
1	30	2	—	—	—
2	24	8	—	—	—
3	8	23	1	—	—
4	15	9	2	4	2
5	15	17	—	—	—
6	19	2	11	—	—
No. of observations	111	61	14	4	2

Fig. 4. Ventilation patterns observed for the patient rooms. (*a*), directions of air flow as designed; (*b*), (*c*), (*d*) and (*e*), other observed air-flow patterns. The table shows the number of times the respective pattern was observed in the specified room.

Over a preliminary period of 32 days it was found that the designed ventilation was not maintained at all times and the frequency of variation is shown in Fig. 4. It can be seen that the commonest fault was a reversal of air flow beneath the door between the airlock and the passage, thus allowing escape of air from the room to the passage. We therefore included this type of ventilation in our experiments and all references to incorrect ventilation refer to this. The direction of air flow was checked before every experiment.

Particle generation

A spinning disk particle generator was used throughout the experiments. The rotation rate of the disk was 60,000 rev./min. and a main air-flow rate of 60 ft.^{3}/min. (1·7 m.^{3}/min.). The satellite air flow removes smaller satellite particles from the main air flow and this was found to operate satisfactorily at 6 ft.^{3}/min. (0·17 m.^{3}/min.).

Potassium iodide dissolved in methyl alcohol and supplied to the spinning disk at a rate of 1 ml./min. gave rise to a particle production rate of c 10^7 particles/min.

Sampling methods

Air sampling was carried out by trapping the particles on 2·5 cm. diameter membrane filters (Millipore Filter Corp.) of 3 μm. pore size. Two types of sampler were used.

(*a*) Where the KI particle concentrations were high, known volumes of air were sucked through the millipore filters. Open-ended plastic filter holders were used (Foord & Lidwell, 1972). Owing to the high air-flow resistance of the filters the maximum air flow obtainable with the pumps which were available was 10 l./min. This was suitable for use with KI particle concentrations of more than 5/l.

(*b*) In situations where there were low particle concentrations the centripetal samplers described by Foord & Lidwell (1972) were used. These were designed to have a collection efficiency of 100 % at flow rates above 60–70 l./min. for 13 μm. equivalent diameter particles (i.e. particles which have the same sedimentation rate as a 13 μm. particle of specific gravity 1). A suction pressure of 20 cm. water gave a flow rate of 100 l./min. and under these conditions only 3 % of the air flow passed through the filter.

Staining. After particle collection the filters were immediately stained with 1 % palladium chloride in 0·1 % HCl.

Counting. Particle counting was performed with the aid of a low-power plate microscope and a grid. Up to 200 particles were counted.

Determination of particle size

Two ways of determining particle size are available:

(*a*) By direct microscopy of particles deposited on a silicone grease coated slide.

(*b*) By calculation of the sedimentation rate and hence the equivalent particle diameter by Stokes Law ($s \simeq 0{\cdot}002d^2$), where the sedimentation rate, s, is in units of m./min., and the diameter, d, is in units of μm.

Methods of calculating the sedimentation rate of airborne particles are described

in 'Studies in Air Hygiene' (Bourdillon, Lidwell & Lovelock, 1948). Two independent methods of determining the sedimentation rate were used. First, from the die-away rate (K), which is the logarithmic rate at which particles disappear, $K \simeq$ slope $\times$ 138/hr. In an unventilated room K is due solely to sedimentation and thus $K = sA/V$, from which the equivalent diameter can be found (A is the area onto which sedimentation is occurring and V is the volume of air from which sedimentation occurs).

Alternatively, the sedimentation rate can be calculated from the number of particles sedimenting onto a known area when the number of particles in a unit volume of air is known. This can be represented as: no. of particles sedimenting $= s \times$ the concentration of particles in the air.

EXPERIMENTAL DESIGN

Preliminary studies to find an appropriate particle size

A small sealed room was used in which particles were generated. Different size particles are produced by varying the concentration of the potassium iodide solution fed to the spinning disk and the concentrations used were 2·0, 3·5 and 5·0%. Particles were generated for 20 min. and 1 l. air samples were taken at 5 min. intervals during this time and for the 20 min. after particle generation had ceased. In addition filters were exposed on the bench for the last 5 min. of particle generation. The concentrations of KI gave particles with the following sedimentation rates: 2·0% = 0·15 m./min.; 3·5% = 0·23 m./min.; 5·0% = 0·31 m./min.

A 5% potassium iodide solution was used for the transfer experiments and this gave particles with a sedimentation rate close to the median found for airborne particles carrying *Staphylococcus aureus* in hospital wards (Noble, Lidwell & Kingston, 1963).

Studies on the transfer of particles from the room to the passage

Since the earlier study had shown the variability of air flow in the ward, it was decided to perform experiments using both the correctly ventilated air locks and also the commonest type of ventilation defect (i.e. that in which the air flow beneath the door between the passage and the airlock was reversed).

The generator was situated in the room chosen and adjusted to give a concentration of 500–1000 particles/l. in the room. There was no activity for the first 30 min. and then, for the following 30 min., one walk from the room to the passage was performed every second min. The dwell time in the airlock was 30 sec. Throughout the experiment samples were taken at the following sites; (*a*) in the room, samples taken at 5 min. intervals; (*b*) in the airlocks, samples were taken at 5 min. intervals during the period of no activity; (*c*) across the passage 2 m. from the room door, 7·5 m. up the passage, 7·5 m. down the passage, and at 15 m. either up or down the passage according to the room in use. These sites are shown in Fig. 1 for the experiments when the generator was in room 1. One 10 min. sample was taken between 20 and 30 min. and then during activity samples were taken at 5 min. intervals.

Particle transfer from passage to room

The generator was situated in the passage about 3 m. from the door of the room to be investigated. The periods of activity and non-activity were the same as before, as was the type of activity. Samples were taken at 1 m. from the door (at 5 min. intervals throughout the experiment), in the airlock (at 5 min. intervals during the period of no activity), and in the centre of the room where one 10 min. sample was taken between 20 and 30 min. and then 5 min. samples were taken continuously during the period of activity. Correct and incorrectly ventilated airlocks were used.

Transfer of particles from the bathroom to the passage

The generator was situated in the bathroom and there was no activity for the first 30 min. of generation, for the next 30 min. there was activity through the airlock I at the rate of one walk to the passage and back every 2 min. There was then a period of non-activity for 15 min. and for the last 20 min. there was activity through the direct door to the passage at the same rate as before. During this time samples were taken in the same six sites as they were in the room to passage experiments and the sampling times were also the same. The only exceptions to this were that no samples were taken in the airlock during the second period of non-activity and only for the last 10 min. of this period in the passage. During the last period of activity samples were taken once every 5 min. in the passage and in the bathroom.

Transfer of particles from passage to the bathroom

Particles were generated at about 3 m. from the bathroom doors which opened into the passage. Samples were taken between these two doors (about 1 m. from each). Samples were also taken in the airlock I and in the bathroom. The activity was the same as that in the bathroom to passage experiments and the sampling was the same as that in the passage to room experiments, except that no samples were taken in the airlock during the second period of non-activity. In the last two experiments correctly and incorrectly ventilated airlocks were used.

In addition to the above samples, blank samples were taken at each site before the start of each experiment.

Calculation of results

In all the experiments the particle concentration at any site started at zero and rose to a steady value in a short time. The steady values were determined by inspection of the data. For the source site, equilibrium was usually achieved within 10 min. of the start of generation, and at the receiving site a steady state was usually achieved after 10–15 min. of walking (depending on the site of sampling). The average particle concentration during the steady-state period was used in all calculations.

The behaviour of ventilation systems of the type under investigation has been studied theoretically by Lidwell (1972), making a number of simplifying assump-

tions. The analysis which follows is based on this study and has been carried out in collaboration with him.

The ratio α of the number of particles at the source to that at the receiving site gives a measure of the effectiveness of the system in protecting the patient from airborne infection, i.e.

$$\alpha = \frac{\text{Concentration of particles in the source room}}{\text{Concentration of particles in the receiving room}}$$

(large values of α indicate a high degree of protection).

Since the passage intervenes between the patient rooms, transfer of particles may be conveniently analysed by breaking the process down into two stages: (1) transfer from the source room to the passage; (2) transfer from the passage to the receiving room.

α' and α'' are used as symbols for these ratios, i.e.

$$(1) \quad \alpha' = \frac{\text{Concentration of particles in the source room}}{\text{Concentration of particles in the passage}},$$

$$(2) \quad \alpha'' = \frac{\text{Concentration of particles in the passage}}{\text{Concentration of particles in the receiving room}}.$$

Similar ratios can be calculated for bathroom to passage transfer and vice versa. Thus

$$\alpha' \text{ (bathroom)} = \frac{\text{Concentration of particles in the bathroom}}{\text{Concentration of particles in the passage}},$$

and

$$\alpha'' \text{ (bathroom)} = \frac{\text{Concentration of particles in the passage}}{\text{Concentration of particles in the bathroom}}.$$

The theoretical calculations predict that

$$\alpha \doteq v_1 v_2 / uv, \quad \alpha' \doteq v_2/u, \quad \alpha'' \doteq v_1/v,$$

where v_1 is the total rate of ventilation (both real and apparent due to sedimentation) in each patient room and v_2 is the total rate of ventilation in the passage (including the effects of sedimentation). v is the rate of air movement from the passage to the room, and u is the rate of air movement from the room to the passage. In addition to any continuous air flows due to incorrect ventilation conditions u and v will include air transferred by movement through the doors. This is related to the frequency of movement through the doors (m) and the amount of air swept through the door in the direction of movement on each occasion (w).

The ventilation input to the patient rooms is 200 m.^{3}/hr. The apparent ventilation due to particles sedimenting at 0·3 m./min. onto the floor area of 16 m.^{2} = $16 \times 0{\cdot}3 \times 60 = 300$ m.^{3}/hr.

Similarly in the passage, the ventilation input is 1100 m.^{3}/hr. and the apparent ventilation when the floor area is 90 m.^{2} is 1600 m.^{3}/hr. The input to the bathroom is 1350 m.^{3}/hr. The apparent ventilation due to a floor area of 30 m.^{2} is 550 m.^{3}/hr.

Hence $v_1 = 200+300 = 500$ m.^{3}/hr.

and $v_2 = 1100+1600 = 2700$ m.^{3}/hr.

and v_1 (bathroom) $= 1350+550 = 1900$ m.^{3}/hr.

For a purely extract-ventilated airlock with air drawn equally from both sides it can be shown that $u = v = mw$ (Lidwell, 1972). However, the actual transfer of particles will be less than this because of the loss of particles by sedimentation within the airlock. The room airlock has a floor area of 4 m.^{2} and an extract ventilation of 100 m.^{3}/hr. The proportion of particles with a settling velocity of 0·3 m./min. lost by sedimentation is then 0·42. If the air was drawn equally from both sides then the effective value of u and v for the transport of particles becomes $(1–0{\cdot}42)mw = 0{\cdot}58mw$.

The bathroom airlock had an air supply of 350 m.^{3}/hr. The extract of air from the bathroom airlock was 440 m.^{3}/hr. Assuming that the difference was drawn equally from both sides 45 m.^{3}/hr. will have come from the passage and 45 m^3./hr. from the bathroom itself. As a consequence $u = v = 45/440 \times 2mw = 0{\cdot}2mw$. The floor area was 5 m.^{2} so the proportion lost by sedimentation was, making the same assumptions as earlier, $(60 \times 0{\cdot}3 \times 5)/(60 \times 0{\cdot}3 \times 5+440) = 0{\cdot}17$. The effective values of u and v for the transport of particles through the bathroom airlock are then given by $u = v = (1-0{\cdot}17) \times 0{\cdot}2mw = 0{\cdot}19mw$.

The experimental value of m was 30/hr. and for the purposes of calculation we have assumed that $w = 1$ m.^{3}.

For the room airlock therefore the predicted value of u and v during the experiments was $30 \times 0{\cdot}58 = 17$ m.^{3}/hr. and for the bathroom airlock $30 \times 0{\cdot}17 = 5$ m.^{3}/hr. For the direct bathroom door the corresponding value would be 60 m.^{3}/hr. (there is no sedimentation loss to allow for in this instance).

Substituting these values in the equations for α' and α'' gives the following results:

(1) room to passage $= \alpha' = \dfrac{v_2}{u} = \dfrac{2700}{17} = 160$;

(2) passage to room $= \alpha'' = \dfrac{v_1}{v} = \dfrac{500}{17} = 29$;

(3) room to room $= \alpha = \alpha' \times \alpha'' = \dfrac{2700 \times 500}{17 \times 17} = 4{\cdot}7 \times 10^3$;

(4) bathroom to passage $= \alpha'$ (bathroom) $= \dfrac{2700}{5} = 540$;

(5) passage to bathroom $= \alpha''$ (bathroom) $= \dfrac{1900}{5} = 380$;

(6) bathroom to room $= \alpha = \dfrac{2700}{5} \times \dfrac{500}{17} = 1{\cdot}6 \times 10^4$;

(7) room to bathroom $= \alpha = \dfrac{1900}{5} \times \dfrac{2700}{17} = 6{\cdot}1 \times 10^4$.

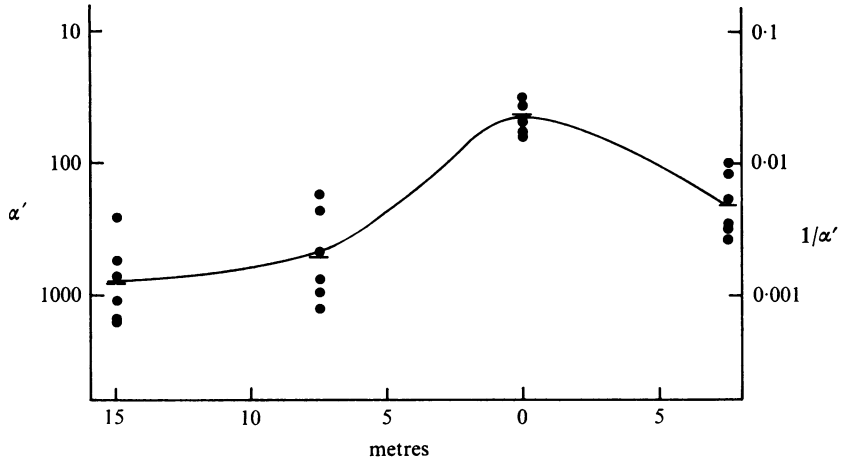


Fig. 5. Distribution of particles along the passage. Source in room 1 with correct ventilation and activity at 30 entries and exits/hr. Right-hand scale is the ratio of the particle concentration in the passage to that in the source room, i.e. $1/\alpha'$. The points show the approximately steady values attained in the individual experiments. The short horizontal bars are the log mean values as given in Table 1.

These values are calculated for the experimental movement through the doors of 30/hr. in each direction. The values of α' and α'' for correctly ventilated airlocks are inversely proportional to m and α is inversely proportional to m^2.
For other values of m

$$\alpha'_m = \alpha'_{30}\,(30/m), \quad \alpha''_m = \alpha''_{30}\,(30/m), \quad \alpha_m = \alpha_{30}\,(30/m)^2.$$

If, however, the ventilation is unbalanced so that there is air flow between passage and room independent of movement of persons through the doors the transport of particles by this air flow is unaffected by a change in the value of movement through the door and

$$\frac{1}{\alpha'_m} = \frac{1}{\alpha'_0} + \left(\frac{1}{\alpha'_{30}} - \frac{1}{\alpha'_0}\right)\frac{m}{30},$$

and similarly for α''.

Where α'_m denotes α' when the movement through the door is m/hr., α'_0 is the value of α' when there is no activity and α'_{30} corresponds to the experimental value of α', when there are 30 entries and exits/hr. through the door, the number employed in the experiments.

RESULTS

Fig. 5 shows the way in which the ratio of particles in the room and passage vary with increasing distance of the sampling site from the room; it also shows variability of the estimates obtained in the several experiments. The values used were obtained from room to passage transfer experiments with a correct ventilation.

The mean values of α' and α'' for the various sampling positions for all the experiments performed are presented in Table 1. The values are log means of at least five experiments. The table also shows the log mean values of α' over all the positions. The corresponding values of α are calculated from these values and also shown in Table 1. As can be seen from the table there is no detect-

Table 1. *Particle transfer within the Burns Unit. Avd. 79A*

Nos.	Transfer	Ventilation	Activity	α' at sampling position 7·5a	2	7·5b	15b	α' Mean	α''	$\alpha = (\alpha' \times \alpha'')$† To P-room	To B-room
1–4	Patient room/ passage	Correct	None	$> 10^5$	$> 10^4$	$> 10^5$	$> 10^5$	$(> 10^5)$	$(> 10^5)$	$> 10^9$	—
		Correct	In/out through airlock	204	45	505	818	245	39	$9{\cdot}6 \times 10^3$	—
		Faulty	None	248	58	226	1200	251	$(> 10^5)$	$> 2{\cdot}5 \times 10^7$	—
		Faulty	In/out through airlock	71	20	46	780	83	66	$5{\cdot}5 \times 10^3$	—
5–10	Bathroom/passage	Correct	None	88	22	297	1050	155	$(>10^5)$	$> 1{\cdot}5 \times 10^7$	$> 10^{10}$
		Correct	In/out through airlock	44	19	173	562	96	215	$3{\cdot}8 \times 10^3$	$5{\cdot}3 \times 10^4$
		Correct	In/out through direct door	39	10	292	741	96	63	$3{\cdot}8 \times 10^3$	$1{\cdot}5 \times 10^4$
		Faulty	None	38	21	151	751	98	$(> 10^5)$	$> 1 \times 10^7$	$> 2{\cdot}5 \times 10^7$
		Faulty	In/out through airlock	39	21	48	480	66	400	$4{\cdot}3 \times 10^3$	$3{\cdot}3 \times 10^4$
		Faulty	In/out through direct door	31	15	79	202	52	66	$3{\cdot}4 \times 10^3$	$5{\cdot}5 \times 10^3$

The values of α' and α'' are, in each case, the log mean values of 5–7 experiments. α' mean = α' averaged over all sampling positions, log mean of 4 values.

† Left-hand column α values for transfer to a patient room; first 4 lines, from another patient room; last 6 lines from the bathroom. Right-hand column α values for transfer from a patient room to the bathroom. In all cases the same activity and type of ventilation is assumed to hold for both source and receiving room.

able transfer of particles from room to passage or passage to room when the ventilation functions correctly, i.e. α' is $> 10^5$, α'' is $> 10^5$. When a steady state has been achieved under activity α' is 245 and α'' is 39. For an incorrectly ventilated room with no activity α' is 251, i.e. about the same value as α' during activity for a correctly ventilated room, and during activity this falls to 83. However, α'' for an incorrectly ventilated room is 66, which is considerably higher than that for a correctly ventilated room. When the source room and receiving room are both correctly ventilated α is $9{\cdot}6 \times 10^3$; the corresponding α for incorrectly ventilated rooms is $5{\cdot}5 \times 10^3$. An incorrectly ventilated source room and a correctly ventilated receiving room gives an α of $83 \times 39 = 3{\cdot}2 \times 10^3$, and a correctly ventilated source room and an incorrectly ventilated receiving room gives an α of $245 \times 66 = 1{\cdot}6 \times 10^4$. The bathroom α' when the airlock is ventilating correctly is rather low, 155; this is due to the fact that particles are always passing from the bathroom into the passage underneath the direct door; because of this α' bathroom due to activity does not vary greatly between correct or incorrect ventilation or activity through the airlock or the direct door. α'' bathroom, however, is lower if the ventilation is correct than if it is incorrect, 215 as opposed to 400. There is also a difference between α'' bathroom if the activity is performed through the airlock or through the direct door. The value of α for transfer from the bathroom to a patient room during activity (entering and leaving the bathroom via airlock I) is $3{\cdot}8 \times 10^3$, when ventilation to rooms is correct. For transfer from a patient room to the bathroom under similar conditions the value of α is $5{\cdot}3 \times 10^4$.

DISCUSSION

As stated above there were two objectives in this work, to obtain an estimate of the degree of protection from airborne cross-infection provided by the ventilation system used in this ward and to compare the experimentally determined values for particle transfer with the values predicted by a theoretical analysis.

Owing to incomplete mixing of air in the passage there was a rapid fall in particle concentration with increasing distance from the door of the source room (Fig. 5). Because of this it is necessary to derive average values of α'. To estimate the average cross-infection risks of all the rooms, the logarithmic mean of α' at the different points was used since the risk of nasal acquisition (and hence the risk of infection) is probably more nearly related to the logarithm of the concentration of bacteria in the air (Lidwell, 1963; Lidwell *et al.* 1971) than to the arithmetic value. To compare the results with theory it is best to take an arithmetic average of the particle concentrations at the sampling points, i.e. the average of $1/\alpha'$ because the points are equidistant along the passage and the theoretical value of α' is based upon the assumption of complete mixing of the air. These values are given in Table 2. This average value was also used to calculate values of u ($u = v_2/\alpha'$). In deriving the experimental value of α' for the bathroom the particle transfer due to air passing beneath the direct door (i.e. $1/\alpha'$ with no activity) was subtracted from the particle transfer when there was activity. It is not possible to estimate the transfer when the ventilation is incorrect as the amount of extra transfer between the room and the passage (or vice versa) is not

Table 2. *Comparison of observed and predicted values (for designed ventilation)*

		α'	u	α''	v
Room (airlock)	Observed value	143	19	39	13
	Predicted value	160	17	30	17
Bathroom (airlock)	Observed value	170	16	215	9
	Predicted value	640	5	450	5
Bathroom (direct door)	Observed value	59	41	63	21
	Predicted value	45	60	23	60

The α' values have been derived as the arithmetic average of the particle concentrations at the different sampling positions, i.e. by summation and averaging of $1/\alpha'$, see text.

Predicted values of u and v assume a value of 1 m.^{3} for w, the volume of air transferred through a door on opening it, passing through and shutting it again.

known. For the room experiments, correlation of predicted and experimental values of α' and α'' is good.

For the bathroom the correlation is not so good but the ventilation of this room was certainly not in accordance with the specification and the leakage under the door into the passage meant that the values of α' had to be derived as a difference between two experimentally determined values. The general closeness of the estimates to the experimental results suggests that the theoretical model is broadly correct, but that errors are present in the estimation. Thus, the value of w is only an approximation and may be subject to considerable variation depending upon thermal difference across the door, size of the door and room, angle to which door is opened etc. Values of v_1 and v_2 were taken from the engineer's plan and in view of the variable ventilation state of the ward may have borne little relationship to the true values of v_1 and v_2. We were unfortunately unable to check the accuracy of the figures.

Experimental errors were due to two main contributions: (1) relatively small air samples were taken; (2) random air movements caused great variation in the particle concentration at different sites. A number of factors caused these air movements, amongst them were thermal currents, disturbances due to opening of doors, movements of staff and uncontrolled day to day variations in ventilation.

Estimation of the cross-infection risk

The estimated value of α for transfer of particles from one room to another with correct ventilation is $> 10^9$ when there is no activity (i.e. transfer of particles was undetectable) and $9{\cdot}6 \times 10^3$ when the rate of activity is 30 walks/hr. However, normal activity in the ward is much less than this and observations in this unit indicate a value of 3–5 door openings/hr., about half that found in a two-bed isolation room (Lidwell & Towers, 1969) and we have deduced that a reasonable estimate of the normal value is 5 walks/hr., i.e. $m = 5$. This leads to an α of $3{\cdot}4 \times 10^5$ between correctly ventilated rooms with normal activity. It would seem that this should provide good protection against cross-infection due to airborne contamination since a value of 1 colony forming unit (c.f.u.)/l. in a source room would give rise to a concentration of only 3×10^{-6} c.f.u./l. in the receiving room. This estimate of the concentration of bacteria-carrying particles in the room is

equivalent to only 0·15 c.f.u. in the whole volume of the room (5×10^4 l) or 1 c.f.u. inhaled every three weeks at an inspiration rate of 10 l./min. If 1/3 m.^{2} of body surface were exposed to contamination by settling and the airborne particles were of the size commonly found (settling velocity 0·3 m./min.) then the dose received in this way would be no more than 1 c.f.u. in 50 hr.

If the airlocks do not function correctly then the value of α will be different. The results of experiments upon the type of incorrectly ventilated airlocks investigated showed that in the absence of all activity α' for a room with an incorrectly ventilated airlock was as much as α' for a room with a correctly ventilated airlock when the level of activity was 30 walks/hr. However, α'' for such an incorrectly ventilated airlock during activity was higher than the corresponding value for a correctly functioning airlock. Thus the worst situation for which we can derive an estimate will be when the source room has an incorrectly ventilated airlock, and the receiving room has a correctly ventilated airlock. With a normal activity of 5 walks/hr the value of α would then be $4{\cdot}4 \times 10^4$. Thus if one airlock is functioning incorrectly the risk in all the other rooms is about ten times greater than under correct conditions, e.g. for a concentration in the source room of 1 c.f.u./l. a patient in a receiving room would inhale 1 c.f.u. every 2 days and about 5 c.f.u. might settle on 1/3 m.^{2} of exposed body surface each 24 hr.

There are two other possible ways in which contaminated air might reach the patient. Large amounts of bacteria may be dispersed during bathing in the bathroom and be transferred throughout the ward. Alternatively the patient might become infected in the bathroom with bacteria transferred from another patient room. In the first case there is continuous contamination of the corridor from the bathroom due to air passing beneath the direct door even when there is no activity through the correctly ventilated airlock. But it is greater when there is activity and when the airlock is ventilated incorrectly. The airlock, however, was usually ventilated correctly, and under normal conditions there was little activity through the airlock and none through the direct door. For the purposes of calculation we have assumed the activity through the bathroom airlock to be 5 walks/hr. although this is probably too high a value. This leads to a value of α for transfer from the bathroom to a patient room of $3{\cdot}9 \times 10^4$. In the second case the value of α for transfer from a patient room to the bathroom, again assuming 5 walks/hr. through the bathroom airlock, would be $1{\cdot}9 \times 10^6$ if the patient room ventilation functions correctly and $2{\cdot}4 \times 10^5$ if the airlock is incorrectly ventilated.

In neither of the above 3 cases is the risk of cross-infection much higher than the risk run by patients when in patient rooms, if one room with an incorrectly ventilated airlock is occupied by a disperser.

Conclusion

It would seem from the above results that, under normal conditions, the isolation system was highly effective at preventing the airborne transfer of particles and even when the ventilation was not operating correctly the particle transfer was very small. Since there has been a considerable cross-infection rate over the past years it would seem likely that other routes of infection have been responsible for this.

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