

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

II. Ventilation in subdivided isolation units

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SUMMARY

Values are deduced for the efficiency of isolation against airborne particulates, e.g. micro-organisms, of a variety of ventilation systems. The calculated values show reasonable correspondence with the limited experimental data available. Much better control and indication of the air flow is necessary if high degrees of isolation are required.

INTRODUCTION

In an isolation unit ventilation may serve any or all of three purposes, to maintain a comfortable environment, to remove smells, to reduce the possibilities of airborne transport of micro-organisms from one patient to another. The criteria for the first two purposes are well known and not difficult to meet. The third, however, is less clear. Epidemiological evidence as to the relevance of airborne infection is generally lacking so that a precise specification cannot be given. It seems likely, however, that if any clinical benefit is to be obtained it will only be gained by reducing the extent of airborne transport by several orders of magnitude. There are very few data on the physical effectiveness of different ventilation systems, but some deductions can be made from a theoretical analysis and these then compared with the scanty material available.

As a simplified model we may consider a number of rooms opening off a communications area (Fig. 1).

EXCHANGE OF AIR BETWEEN ROOMS

In calculating the transport of particles from the air exchange between the parts of a system, it is convenient to assume that turbulent air mixing within each room is sufficient to produce a substantially uniform concentration of particles within it. This is a satisfactory approximation so long as the spaces involved are not too large or unusually shaped.

In assessing the performance of any system it is more realistic to compare it with the situation in which all the patients are housed in one room having the same

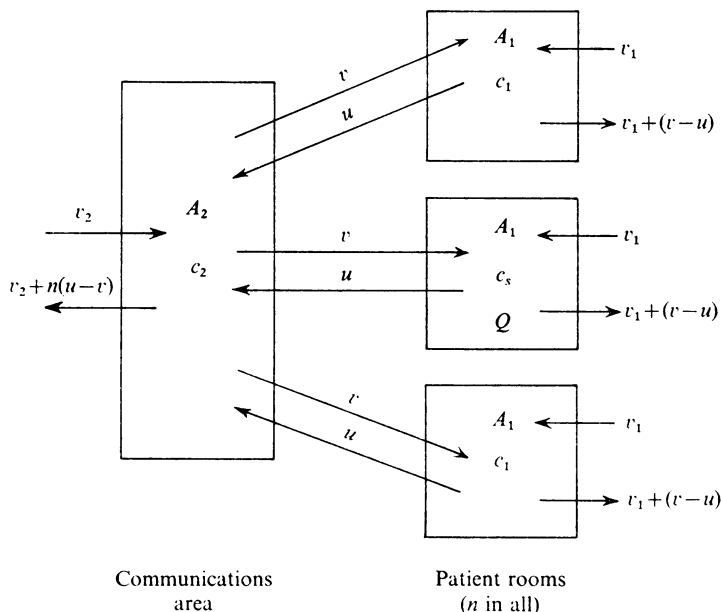


Fig. 1. Schematic diagram of the system analysed. The arrows show the directions of the air movements between the n patient rooms and the communications area together with the air supply and consequent exhaust. The symbols u and v , with suffixes as appropriate, indicate the volumetric rates of air movement, for example in m^3/hr . Symbols c_1 , c_2 denote the equilibrium particle concentrations arising from a source, Q particles per unit time (e.g. per hr.), in one patient room where the equilibrium concentration is c_s . A_1 and A_2 are the floor areas (more properly the aggregate areas of the horizontal surfaces on which particle sedimentation takes place) of the rooms.

total ventilation and floor area than just to compare the particle concentration in a room housing a source with that in the other patient rooms. The ratio of these concentrations, α in equation (5) below, which is all that is available for measurement by observations made within the system itself, gives an unduly favourable estimate of the efficiency of the isolation since the particle concentration in the source room is increased when the source is contained in a small room.

If, then, there is a source generating Q units of particle contamination/hr. in one of the rooms of the system shown in Fig. 1 the following equations will define the equilibrium state, neglecting the effect of particle settling

$$c_s (v_1 + v - u) + c_s u = v c_2 + Q, \quad (1)$$

$$c_1 (v_1 + v - u) + c_1 u = v c_2, \quad (2)$$

$$c_2 (v_2 + n (u - v)) + c_2 n v = u c_s + c_1 (n - 1) u, \quad (3)$$

where the symbols have the meaning shown in Fig. 1.

In addition if the system were replaced by a single space with a floor area and ventilation supply equal to the sum of those of the individual rooms and the communications area then the equilibrium state would be defined by

$$c_m (v_2 + n v_1) = Q. \quad (4)$$

This value of the particle concentration, c_m , is the value to which c_s , c_1 and c_2 all tend as u and v both become very large but $v \sim u$ remains small.

From equations (1)–(4) it is easy to deduce that

$$c_s/c_1 = \alpha = 1 + (v_1 v_2 + v_2 v + n v v_1)/uv, \quad (5)$$

$$c_m/c_1 = \beta = (v + v_1) (v_1 v_2 + v_2 v + n v v_1)/uv (v_2 + n v_1). \quad (6)$$

If both u and v are small relative to v_1 and v_2 then

$$\alpha = c_s/c_1 \simeq v_1 v_2/uv, \quad (5A)$$

$$\beta = c_m/c_1 \simeq v_1 v_1 v_2/uv (v_2 + n v_1), \quad (6A)$$

and

$$\alpha/\beta = c_s/c_m = n + v_2/v_1. \quad (7)$$

In addition

$$c_s/c_2 = \alpha' = 1 + (v_1 v_2 + v_2 v + \overline{n-1} uv_1)/u (v_1 + v), \quad (8)$$

$$c_2/c_1 = \alpha'' = 1 + v_1/v, \quad (9)$$

or if both u and v are small as before

$$\alpha' = c_s/c_2 \simeq v_2/u, \quad (8A)$$

$$\alpha'' = c_2/c_1 \simeq v_1/v. \quad (9A)$$

In all the above equations u and v , the volumes of air passing between the individual rooms and the communications area, include air movements due to imbalance in the air supplied to or extracted from the rooms, air exchange across the doorways or other openings as a result of thermal differences and air exchanged across doorways when the doors are opened and shut and when people pass through them.

The effects of particle size

In addition to the effects of ventilation, the particles carrying the micro-organisms will be settling under the influence of gravity. The effect of this on the dispersal and air-concentration of the particles is equivalent, under conditions of complete turbulent air mixing within the individual rooms, to adding to the clean air input into any room a quantity As , where A is the floor area of the room concerned and s is the effective settling velocity of the particles. For bacteria-carrying particles the value of s is usually close to 0.3 m./min. (Noble, Lidwell & Kingston, 1963).

Transport through airlocks

In order to apply the results of the preceding section to systems which include airlocks, with doors to both the patient room and the communications area, it is necessary to obtain some estimate of the effective transfer of air through them when a person enters or leaves the room, i.e. of the rate of direct transfer of air from the room to the corridor, or in the reverse direction, that would transfer the same amount of airborne contamination as that effected by passage through the airlock. These estimates can then be introduced into equations 5–9 as the appropri-

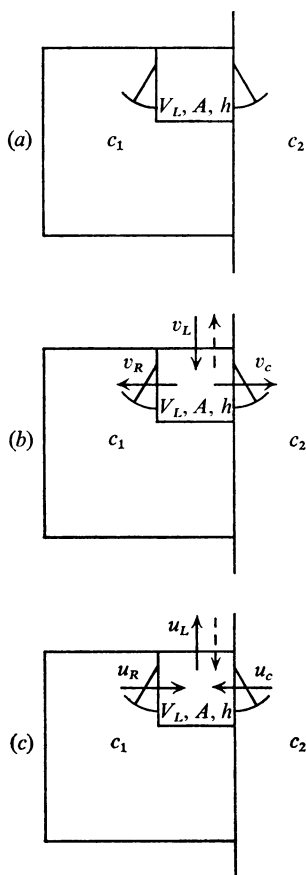


Fig. 2. Airlocks. Symbols c_1 , c_s and c_2 , as in Fig. 1, denote the equilibrium particle concentrations in the n patient rooms and in the communications area. V_L is the volume of an airlock, A its floor area and h its internal ceiling height. (a) Unventilated airlock. (b) Input ventilation at v_L of which v_R passes into the patient room and v_c into the communications area. (c) Extract ventilation at u_L of which u_R is drawn from the patient room and u_c from the communication area.

ate values of u and v . Three situations are illustrated in Fig. 2: (a) an unventilated lock; (b) a lock with clean air input; (c) a lock with extract.

The direction of air flow around the door edges with a balanced ventilation system and an unventilated lock are indeterminate. If there is no flow in either direction when the doors are shut then $u = v = mw^2/V_L$, when there are both m entries into the room and m exits from the room through the airlock in unit time, w is the volume of air exchanged across a door opening each time a door is opened and shut and V_L is the cubic volume of the lock. Loss by sedimentation within the lock is small, a dwell time of about 6 min. would be necessary to halve the concentration of particles within the lock even if it were no more than 2.5 m. high, given the assumed settling velocity of 0.3 m./min. A consequence of this slow die-away, however, is that particles already introduced into the lock may be transferred by a subsequent passage through. For an assumed rate of five passages/

hr. in each direction, one in either direction every 6 min., this will approximately treble the particle transfer,

$$u = v = mw^2/V_L (1 + \frac{1}{2} + \frac{1}{4} + \dots + \frac{1}{2} + \frac{1}{4} + \dots) = 3mw^2/V_L.*$$

In practice there will almost certainly be a flow in one direction or the other, due to residual imbalance in the ventilating system so that either u or v will be many times larger than this figure.

For locks with clean air input greater than any extract, the air in the lock will be clean in the absence of any passage through. Even with an input of 200 m.³/hr. into a lock of volume 10 m.³, 80% of any contamination introduced on entering the lock will remain after a dwell time of 0.01 hr.; but this is of no significance, since any contamination introduced by opening doors will be distributed to the two sides of the airlock in proportion to the air flows. The effect of this is identical in whichever direction a person passes through the lock, so that $u = 2mwv_C/v_L$ and $v = 2mwv_R/v_L$. If there is no extract and $v_C = v_R = \frac{1}{2}v_L$ then $u = v = mw$. Loss by settling during the time taken to flush the contamination out of the lock will however reduce the effective particle transfer. The proportion so lost by settling is given by $60sA/(60sA + v_L)$. If the air input is 100 m.³/hr., the settling area within the lock is 4 m.² and s is taken as 0.3 m./min. then the proportion so lost = $72/(72 + 100) = 0.42$. If $v_C = v_R = \frac{1}{2}v_L$ then as far as the transport of particles through the airlock is concerned effectively $u = v = (1 - 0.42)mw = 0.58mw$. The net air input to the lock must be regarded as additional ventilation air to the system, divided according to the proportionate air flows in the two directions (i.e. v_R is to be included in v_1 and nv_C in v_2). Any contamination produced by activities within the airlock, e.g. putting on or taking off protective clothing etc., will be carried both into the room and into the communications area in proportion to the air flows, subject to losses from sedimentation similar to those described above.

The air within an airlock with extract in excess of any input is always contaminated from both sides in proportion to the relative input flows from both sides. Dwell time in the lock is therefore again irrelevant, since it is not entry into the lock that introduces the airborne particles. On entering or leaving the lock, particles are transferred across the door concerned, hence $u = 2mwu_R/u_L$ and $v = 2mwu_C/u_L$. If there is no input and $u_R = u_C = \frac{1}{2}u_L$ then $u = v = mw$. The continuous loss by sedimentation within the airlock will reduce this to a similar extent to that given above for the positive input situation substituting u_L for v_L . Contamination produced by activities within the lock itself will be transferred in the direction of subsequent passage. With little effect from any dwell time of less than 2-3 min., the fraction will approximate to w/V_L , usually substantially less than the amount transferred from a positively ventilated lock.

Further reduction in the transfer through an airlock can be obtained by a high

* This assumes that w/V_L is sufficiently small for the reduction in concentration of particles left in the airlock each time a volume w is lost on opening a door to be negligible. If w/V_L is as large as 1/10 when the other conditions are as assumed above then the values of u and v will be reduced to approximately $2.2mw^2/V_L$.

rate of near balanced ventilation to the lock, or recirculation through a filter within it. The advantage gained will depend upon the recirculation rate, the time during which recirculation is applied, if not continuous, and the type of airlock involved.

For a lock with positive supply v_L in addition to recirculation at a volumetric rate R , applied on entry to the lock, transfer on passage in the forward direction is reduced to approximately $mw(w/V_L + v_R/(R + v_L))$ for rapid passage through and to $mwv_R/(R + v_L)$ if the dwell time is sufficiently long. Return through the lock will also transfer $mwv_R/(R + v_L)$ in the same direction irrespective of dwell time, i.e. $v = mw(w/V_L + 2v_R/(R + v_L))$ for rapid passage, dropping to $2mwv_R/(R + v_L)$ with sufficient dwell time. Transfer in the reverse direction, u , will be determined by replacing v_R by v_C in the above formula. As an example, if recirculation at 2000 m.³/hr. is applied to a lock of volume 10 m.³ with $v_C = v_R = 50$ then the transfer on rapid passage is $mw(0.1w + 100/2100) = mw(0.1w + 0.048)$. With this rate of ventilation the effects of sedimentation are negligible and the residual concentration in the lock is reduced to about 12% after a dwell of 0.01 hr. Transfer on passage is then reduced to $mw(0.012w + 0.048)$ which is insignificantly different from that resulting from indefinitely long dwell time, i.e. $0.048mw$, since w is likely to be of the order of 1 m.³ (see below). The effects of recirculation applied continuously are identical with those obtained with operation only on entering the lock.

If there is extract from the lock, continuous recirculation will reduce transfer to $u = 2mwu_R/(R + u_L)$ and $v = 2mwu_C/(R + u_L)$ irrespective of dwell time. If the recirculation is switched on only on entry into the lock, the recirculation will have no effect on transfer by rapid passage, and the transfer rate can be no more than halved even with prolonged dwell time.

By the use of directed downward flow ventilation in the airlock nearly 100% clearance could be obtained in a single air pass. At a velocity of 0.5 m./sec. this would take little more than 5 sec. If, however, the floor area of the airlock were 5 m.² the air supply rate would then need to be some 9000 m.³/hr. or 150 m.³/min.

Calculated transfer values

The relationships discussed above may be applied to an infinite variety of possible systems. For illustrative purposes the results obtained for a series of variations on a single layout, using plausible values for the various parameters, have been set out in Table 1. The assumptions of complete and uniform mixing within each space and of uniform regular entries and exits to the several rooms are manifestly approximations so that the precise numerical values must be treated with reserve.

In addition to selecting values for the physical dimensions of the system and for the rates of ventilation, it has also been necessary to assume values for m , the number of passages in each direction between a room and the communications area and for w , the volume of air exchanged between the two sides of a door when it is opened and closed in quick succession.

One study of a two-bed isolation room (Lidwell & Towers, 1970) has shown an

Table 1. Calculated reductions in exposure to airborne particle transfer

Condition	u	v	α	β
A. Balanced supply (no airlocks)	1000	1000	11 (6)	2 (1.7)
	500	500	28 (11)	4 (2)
	200	200	80 (34)	7.5 (4)
	100	100	230 (90)	19 (9)
	50	50	800 (270)	60 (21)
B. Directional flow (no airlocks)	500	10	0.9×10^3	65
	200	10	1.4×10^3	100
	60	10	3.3×10^3	220
	10	500	0.6×10^3	73
	10	200	1.0×10^3	100
	10	60	2.9×10^3	220
C. Airlocks				
Unventilated:				
(a) balanced	[1.5	1.5	6.7×10^5	4.7×10^4]
(b) with directional air flow	{ 50	1.5	2.0×10^4	1.4×10^3
	{ 1.5	50	2.0×10^4	1.4×10^3
(All with allowance for sedimentation in the airlock)				
Ventilated:				
input or extract with allowance for sedimentation	5	5	6.0×10^4	4.2×10^3
	2.9	2.9	1.8×10^5	1.3×10^4
D. Airlocks with recirculation				
Input ventilation				
(a) rapid passage	0.75	0.75	2.7×10^6	1.9×10^5
(b) 0.01 hr. dwell	0.24	0.24	2.6×10^7	1.8×10^6
Extract ventilation				
(a) rapid passage	2.9	2.9	1.8×10^5	1.3×10^4
(b) 0.01 hr. dwell	1.5	1.5	6.7×10^5	4.7×10^4
Directed ('laminar') flow	$\rightarrow 0$	$\rightarrow 0$	$\rightarrow \infty$	$\rightarrow \infty$

The table shows values of the ratio, α , of particle concentration in the source room to that in other patient rooms, and the ratio, β , of the concentration if all the rooms were combined into one space with uniform mixing throughout to the concentration in non-source patient room for the particular system, i.e. the larger the figure the better the isolation. u and v , the air flows from each room into the communications area and in the reverse direction are given in m.³/hr.

The following values have been used in the evaluation of α and β , particle settling velocity 0.3 m./min. Ten patient rooms each with floor area 15 m.² and air input at 300 m.³/hr. (this corresponds to a ventilation rate of 6/hr. for a room height of 3 m.). Settling in these rooms is then equivalent to an additional clean air supply of $0.3 \times 60 \times 15 = 270$ m.³/hr., hence $v_1 = 300 + 270$ and has been taken as 600 m.³/hr. The communications area covers 80 m.² with an air input of 1200 m.³/hr. (this corresponds to a ventilation rate of 5/hr. for a ceiling height of 3 m.). Settling in this area is equivalent to an additional clean air supply of $0.3 \times 60 \times 80 = 1440$ m.³/hr., hence $v_2 = 1200 + 1440$ and has been taken as 2500 m.³/hr. Entries and exits to and from each room have each been taken as 5/hr. ($m = 5$) and 1 m.³ of air has been assumed to be exchanged across the door opening each time a door is opened and shut. The volume of an airlock has been taken as 10 m.³ with a floor area of 4 m.² and with 100 m.³/hr. input or extract when appropriate. When the airlock is ventilated the air has been considered as delivered to or taken from both sides of the lock in equal amounts. Recirculation has been taken as 2000 m.³/hr. and assumed to come into operation only on entering the locks. The figures in parentheses in group A relate to conditions of negligible ventilation supply to the system. The values for the unventilated airlock have been enclosed in square brackets since this condition is practically unrealizable unless sealed doors are used.

average of 360 openings of the room door, entries or exits, per 24 hr. or 15/hr. ($m = 7.5$). Observations on single rooms in a burns unit (Hambraeus & Sanderson, 1972) gave a figure of about half this for a burned patient and rather more for an amputee. It would therefore seem reasonable to take a value of 10 exits or entries/hr., i.e. $m = 5$, for the number of passages/hr. in each direction.

There do not appear to be any published data available on the exchange of air through a doorway on opening and closing the door. Since the volume swept out by a hinged door of conventional size is of the order of 1 m.^3 this figure has been taken as an approximation for the purposes of calculation.

Unpublished experiments carried out recently by the Building Services Research Unit of Glasgow University (W. Whyte & B. Shaw, personal communication) indicate values of 0.5 m.^3 for the air transfer on opening a swing door of conventional dimensions. The figure is substantially less for a sliding door, but the large gaps around such doors may lead to significant air exchange across the closed door unless there is sufficient directed air supplied to swamp reverse convective air flow.

In general hospitals in Britain the doors of patient rooms without airlocks are commonly found to be left open for considerable periods of time (Baird, 1969; N. Foord & O. M. Lidwell, to be published). There have been several published studies of air exchange through open doors or similar apertures as a consequence of small temperature difference (Wolf, Harris & Hall, 1961; Brown, Wilson & Solvason, 1963; Kethley, 1966; Ma, 1965). Unfortunately the numerical values given by the different authors are not in agreement. They range from 40 to $1100 \text{ m.}^3/\text{hr.}$ for a temperature difference of 1° C. across a $2 \text{ m.} \times 1 \text{ m.}$ doorway, with as much as $350 \text{ m.}^3/\text{hr.}$ for only 0.1° C. temperature difference in one instance. Since the air flow, theoretically, is proportional to the square root of the temperature difference quite high air flows may result from very small differences and values of between 100 and $500 \text{ m.}^3/\text{hr.}$ seem not unlikely in practice.

DISCUSSION

With balanced or natural ventilation systems (group A, Table 1) values of α might be expected to lie between 10 and about 250. The actual advantage of subdivision compared with the exposure expected if all the patients were in a single room, given by the value of β , is, as explained earlier, much less, a reduction of between 2- and 20-fold in exposure to airborne particles. Comparison with the limited experimental results available, given in Table 2, shows a reasonable correspondence with the calculated figures. The degree of isolation obtained was, as would be expected, markedly less and the probable extent of air exchange between the parts of the ward much greater in the first situation referred to in Table 2. In this hospital the ward was partitioned but the patient areas opened directly off the communications corridor, being separated from it by no more than a low wall less than 1 m. high.

The introduction of a substantial directional flow to swamp the convective exchange (group B, Table 1) raises the value of α to around 10^3 and β to about 100

Table 2. *The exposure to airborne particle transfer observed in some hospital situations*

Ref.	System	Conditions	Tracer	v_1	v_2	u or v	α
A. Natural and balanced							
1	Partitioned ward	Natural ventilation	<i>Staph. aureus</i>	—	—	(1400)	5
2	Divided ward	Natural ventilation	<i>Staph. aureus</i>	—	—	(600)	10
3	Divided ward	Natural ventilation	<i>Staph. aureus</i>	—	—	(200)	40
4	Divided ward	Natural ventilation	<i>Staph. aureus</i>	—	—	(400)	18
5	Divided ward	Part mechanical ventilation	Nitrous oxide	50–200	4000	100–170	70–80
5	Divided ward	Air conditioned	Nitrous oxide	700	4000	300	80
B. Directional flows							
6	Isolation unit	Positive rooms	<i>Staph. aureus</i>	350	‡1500	20	500
7	Divided ward	Positive rooms	<i>Staph. aureus</i>	800	2500	*	14
7	Divided ward	Positive rooms	Freon gas	800	2500	50	100
7	Divided ward	Positive rooms	Pot. iodide particle	800	2500	50	400
C. Airlocks							
8	Isolation unit	Extract airlocks	Pot. iodide particle	200	1100	2.9	3.4×10^5
8	Isolation unit	Extract airlocks	Pot. iodide particle	200	1100	17	9.6×10^3

The table shows the observed values of α , the ratio of the particles concentration in the source room to that in other patient rooms. The values of v_1 , the ventilation supply to a patient room and v_2 , that to the communication area, both given in m.³/hr., are usually only rough estimates based on limited information. Values of u or v , also in m.³/hr., have been deduced from the above using equation 5. For the balanced and natural ventilation system u and v are assumed equal. For references 6 and 7 u has been taken as 200 and 400 m.³/hr. respectively and the values given in the 7th column are those calculated for v . Where the tracer is particulate v_1 and v_2 have been doubled to allow for sedimentation (this is true if $s = 0.3$ m./min., $h = 3$ m. and ventilation is at 6 changes/hr.) before applying the formula. No estimates of v_1 or v_2 can usefully be made for the first four situations listed. The values of u and v given in parentheses are deduced from those given in Table 1 for the no ventilation condition.

The two values of u , v and α for reference 8 refer to 10 and 60 entries/exits per hr. respectively ($m = 5$ and $m = 30$).

* The discrepancy between the value of α in this row and that for the same system with a similar-sized tracer particle in the row below, suggests that the micro-organisms reached the non-source rooms by other routes than air transfer.

References. 1, Lidwell *et al.* (1971); 2, Lidwell *et al.* (1966); 3, Williams (1967); 4, Edmunds (1970); 5, Baird (1969); 6, Williams & Harding (1969); 7, Foord & Lidwell (to be published); 8, Hambræus & Sanderson (1972).

(this assumes the figure of 10 entries or exits to or from the room in each hour transferring 1 m.³ of air with each door opening). The observed ratios (group B, Table 2) are not quite as high as this and correspond to transfer against the direction of air flow of 20–50 m.³/hr., 2–5 times the assumed figure. This would suggest that the directional flows were inadequate to prevent reverse flow. The insertion of an airlock between the room and the corridor, group C, further increases the ratio α to between 10^4 and 10^5 , on the same assumptions of the frequency of door opening and the extent of air transfer associated with this. The calculated

performance for a ventilated airlock is independent of any delay or dwell on passing through the lock. Extract from the lock has the advantage of reducing dispersal of any airborne contamination generated within it. The one set of figures available in Table 2 show quite close agreement with the theoretical calculations and are presented in greater detail in the next paper (Hambraeus & Sanderson, 1972).

By using high volume recirculation in an airlock it should be possible to increase the value of α to very high values indeed but these could be realized in practice only if transfer of particles by other means than free air, for example on clothes or in the respiratory system, was kept to similarly low levels.

The clinical significance of these calculations and observations is quite uncertain since in no situation have we precise knowledge of the risk of infection by the airborne route as a function of exposure. It is, however, desirable that whenever studies are made of the clinical value of an isolation system measurements of the airborne particle transfer within it should be made under working conditions and that, if a high level of air isolation is considered desirable, the design should be such as to produce this. In order that any system may function effectively the actual air volumes and balances must be stable and correspond to those called for by the design. This is not generally the case, and most systems that I have examined have been both variable and divergent from their design intentions, for example the isolation unit referred to in reference 8 (Table 2) was designed for an input of 200 m.³/hr. to each of the patient rooms with an extract of 100 m.³/hr. from the airlock, supplied as to 50 m.³/hr. from the room and 50 m.³/hr. from the corridor. The value of α given in the table was obtained as between rooms where these flows were, at least approximately, maintained. However, out of 27 observations of the air flow around the doors into the air locks made on six separate days the *direction* of flow was reversed around one or other door on no fewer than 11 occasions. Hambraeus & Sanderson (1972) report similar observations. It must always be difficult to maintain the balance between flows as small as the above and if it is to be achieved some stabilizing factor, for example a relatively high-pressure drop across a filter or control orifice, must be included in the system. In addition, visual or other indicators of the flow directions are called for to ensure maintenance of the design conditions.

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