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Airborne infection in a fully air-conditioned hospital

I. Air transfer between rooms

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SUMMARY

Measurements have been made of the extent of air exchange between patient rooms in a fully air-conditioned hospital using a tracer-gas method.

When the rooms were ventilated at about six air changes per hour, had an excess airflow through the doorway of about 0·1 m.³/sec. and the temperature difference between rooms and corridor was less than 0·5° C., concentrations of the tracer in rooms close to that in which it was being liberated were 1000-fold less than that in the source room. This ratio fell to about 200-fold in the absence of any excess airflow through the doorways. Considerable dilution took place along the corridors so that the concentration fell by around 10-fold for every 10 m. of corridor.

INTRODUCTION

The design and construction of a fully air-conditioned hospital in S.E. London provided an opportunity to study the extent to which the ventilation system could be applied to minimize the airborne transport of micro-organisms from room to room within the building. It would then be of considerable interest to observe the effect on the transmission of bacteria between patients. The investigations reported in this and succeeding papers examine the movement of air from room to room, the transport of airborne particles by this movement, the numbers of airborne particles carrying *Staphylococcus aureus* in the air of the patient rooms in relation to the probable sources of the individual strains and the rates of nasal acquisition by patients of new strains of this organism from carriers nursed in different rooms or wards.

The Greenwich District general hospital was designed by the Design Unit of the Department of Health and Social Security (Drury & Skegg, 1969). It is a four level deep-plan building with several light wells.

Air conditioning is necessary in a building of this kind in order to control internal temperatures and humidities and all areas are supplied from central plant. A cross-sectional view of part of the hospital, showing the ventilation system is given in Fig. 1. Air for ventilation is taken in at roof level and fed through ducts in the inter-floor space into the hospital working area via ceiling diffusers which are designed to mix the incoming air with that already present. Air is removed through extracts at floor level directly into the inter-floor space below and is exhausted to the outside by large perimeter fans. The air supplied to the hospital is 100% fresh

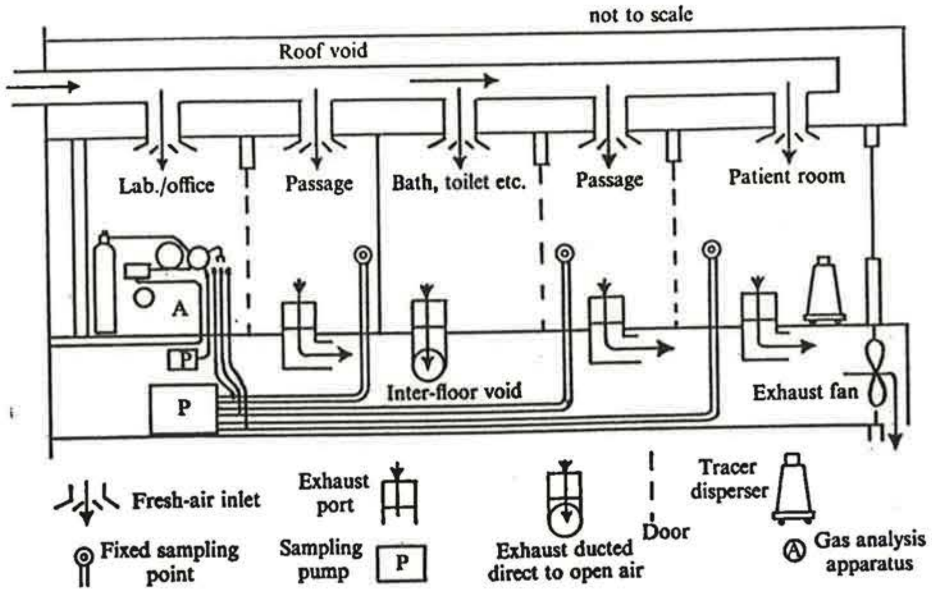

Fig. 1. Section of the medical ward floor showing the ventilation system and the fixed sampling connexions.

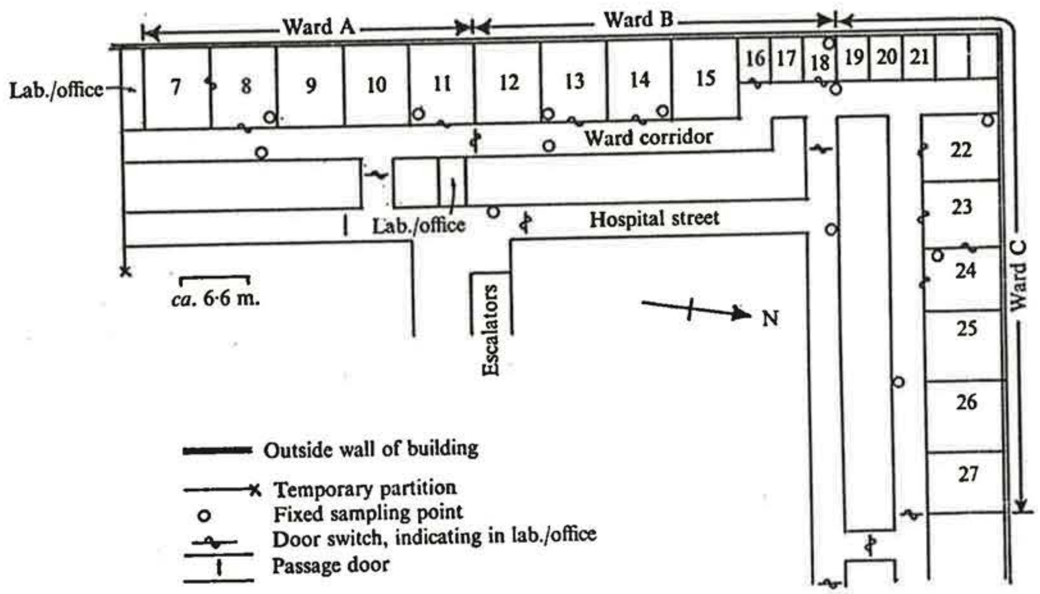

Fig. 2. Plan of part of the medical ward floor showing location of the fixed sampling points and the indicating and recording switches attached to certain doors. Rooms 7–11, 12–15, 22–27 had six beds each, rooms 16–21 were single bed rooms.

air. Most of the general patient areas are designed to have between five and seven air changes per hour. In order to reduce the movement of air between rooms the system was designed to maintain the corridors at a slightly higher air pressure than the patient rooms. This pressure difference was controlled by adjustable flap valves on the extracts.

The area chosen for investigation consists of three subdivided medical wards. A plan is given in Fig. 2. The six-bed patient rooms are situated on the perimeter of the building. The ward corridor and hospital street are both continuous around the hospital and between them are situated the ancillary rooms. All the rooms have hinged doors (approx. 2 m. × 1 m., with an additional leaf for moving large objects) and there are double doors in the corridors which separate the ward units from each other and from the core of the building, which contains all means of vertical communication. The patients in Ward A are female, Ward B contains high dependence male and female patients and Ward C male patients only. There are single patient rooms attached to both Wards B and C. Throughout the investigation, no attempt was made to alter the normal routine of the hospital but rather to observe it under normal operational conditions. A preliminary report has been published by Lidwell & Brock (1973).

METHODS

The air-transfer measurements were made by gas-tracer techniques using the method described by Foord & Lidwell (1973). Either freon 12, freon 114 or BCF was liberated from a portable disperser placed at the desired source position. The concentration of this tracer in an air sample taken at the recipient position was determined using a peak-height calibrated electron-capture detector. In order that all three tracers could be used simultaneously from different source positions, a 2 m. column containing 20 % squalane on a celite base preceded the detector and separated the different tracer-gases in the air sample. The concentration of each tracer-gas in a single sample was then easily measured.

Although there were slight variations in particular circumstances, the general mode of use was to release a tracer-gas continuously at a known, constant, rate at the source position. At least one hour was then allowed for equilibrium conditions to become established. After this period, air samples were taken at all recipient sites and the concentration of the tracer-gas in each was measured. Knowing both the rate of dispersal of the tracer-gas and the equilibrium concentration at each recipient site, the transfer index* to each of the sites was calculated (Lidwell, 1960). The ratio of the transfer index to the room containing the source, to the transfer index to another room is equal to the relative concentration of the tracer-gas in the two rooms.

Conditions in the hospital were never entirely stable during any period of measurement so that no true equilibrium could be attained. During the first series of measurements, between March and June 1971, a representative selection of sites

* The transfer index is numerically equal to the equilibrium concentration divided by the rate of dispersal.

was chosen and sample tubes laid from these rooms through the inter-floor space back to the central office containing the gas analyser. A suction system was installed allowing a sample to be taken from any chosen room containing a sampling tube. Samples from any one particular site were repeated until a constant average concentration was obtained. This was taken to be the equilibrium concentration.

During the second series, between June and August 1973, integrating gas samplers were also used. Each of these consisted of a 50 c.c. glass syringe barrel held vertically and stoppered with a PTFE (polytetrafluoroethylene) bung through which passed a piece of 0·3 cm. o.d. stainless steel tube reaching to near the bottom of the barrel. The barrel was filled with water which escaped at a constant rate through a hypodermic needle (0·5 mm. i.d. × 38 mm. long) attached to the nozzle. The air sample entered via the steel tube and was held in the barrel until analysed. The size of the needle was such that it took approximately 1 hour to obtain a complete air sample. The concentration of the sample therefore represented the average concentration during the sampling hour. In each series, each of the three tracer-gases was used in turn in each room so that three different determinations of the transfer of air from each room were made. This randomized any effect of possible differences between the tracer-gases and between one time and another.

Because of the relatively high concentration of tracer-gas within the source room and because of concentration variations within this room it was difficult to obtain accurate and representative air samples. On most occasions, therefore, the ventilation rate of the room was determined. Following measurements of concentration during liberation of the tracer-gas, the decay of concentration of tracer within the source room was measured, after liberation of gas had ceased, by taking samples at known times either by using the centralized sampling system or by using a glass syringe to collect the air samples. From the rate of decay, the ventilation rate in the source room was determined and the transfer index calculated knowing the size of the room (Lidwell, 1960).

Hospital ventilation and activity monitoring

It was important to measure the actual ventilation within the hospital before examining its effect upon air transfer. The most important characteristics of each room for this purpose were the ventilation rate and the flow of air through the doorway. The former was measured using the tracer methods already described. Regular estimates of the flow of air through the doors between the patient rooms and the corridor were made by determining the relative pressure of the room, whilst the door was closed, with respect to the corridor using a highly sensitive pressure transducer (Shaevitz PTD-3G). By comparison with a previously established calibration curve obtained with a direct reading anemometer (Foord, 1973), this provided a quick and reasonably accurate method for determining the airflows on a routine basis. The air flows through the doorways at any time and the directions of airflow in the corridors were naturally strongly dependent on whether individual doors were open or closed. In order to keep track of the situation in this

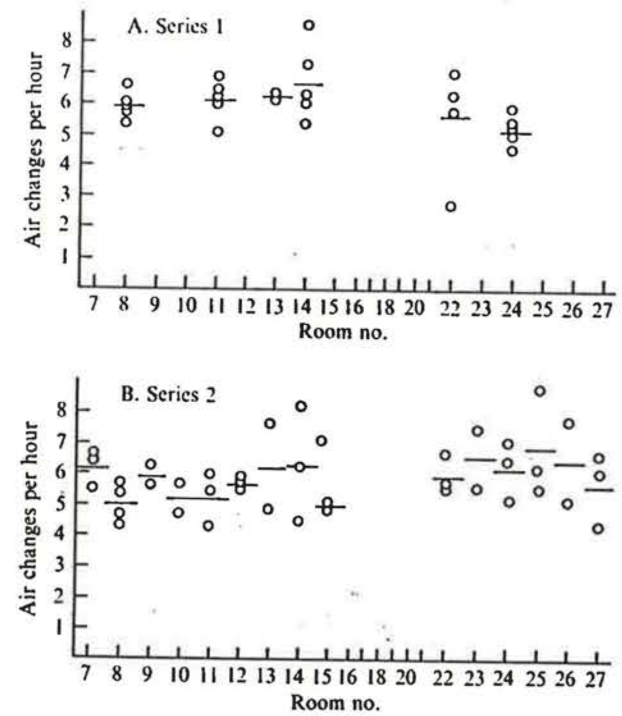

Fig. 3. Observed room ventilation rates. (A) Series 1, March–June 1971. (B) series 2, June–August 1973. The rooms are shown spaced linearly along the horizontal axis. Horizontal bars show mean values for each room.

respect magnetically operated switches mounted on the doors of those patient rooms with fixed sampling points, and on the passage doors, were wired back to an indicating and recording panel in the central office. Records were kept of the average time during which doors were open and care was taken to avoid concentration measurements during uncommon combinations of door openings which had been found to affect the results significantly.

RESULTS

Ventilation rates and doorway airflows

Figs. 3 and 4 give the results of the measurements. The ventilation rates for the patient rooms usually lay between five and seven air changes per hour. Although the original design concept specified that air should flow from the corridor into all the patient rooms this was not realized when the building was first brought into use. As can be seen from Fig. 4A the flow was generally in the opposite direction, especially in the rooms at the South end of the section studied. This was partly due to the unfinished state of the building but principally because of unexpectedly high air resistance in the grilles over the exhaust ports in the rooms and corridors. During the later part of the investigation these grilles were replaced by others with a lower air resistance and this together with some adjustments to the air-supply system produced the near balance condition shown in Fig. 4B.

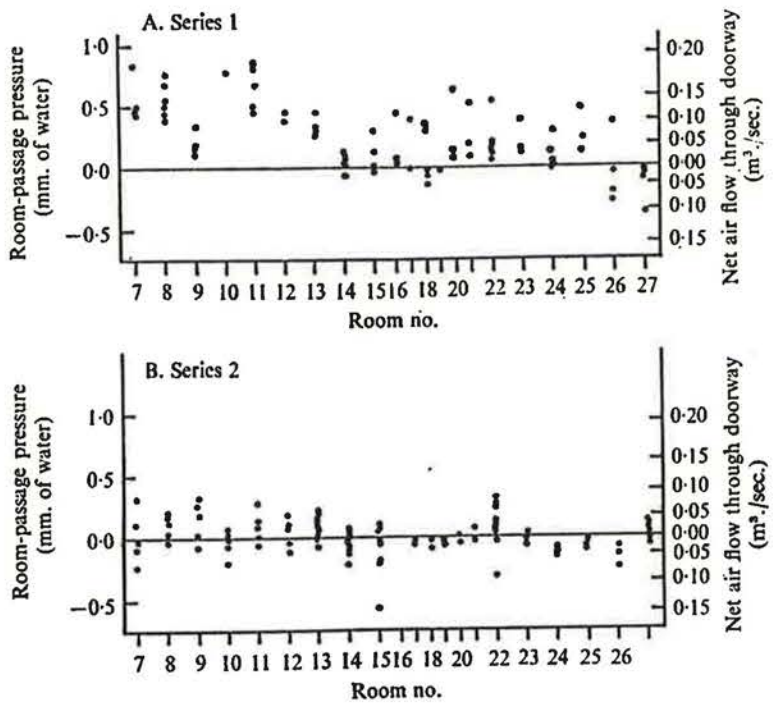

Fig. 4. Room-corridor pressure differences and the corresponding airflows through the doorways. (A) Series 1, March–June 1971. (B) series 2, June–August 1973.

Table 1. *Average conditions of the rooms in each ward during each series of air-transfer measurements*

	Ward A		Ward B		Ward C	
	Series 1	Series 2	Series 1	Series 2	Series 1	Series 2
Number of rooms	5		4		6	
Volume of rooms (m.³)	137		144		138	
Ventilation rate (air changes/hr.)	6·0	5·6	6·5	6·5	5·5	6·2
Pressure relative to corridor (door closed) (mm. H_2O)	+0·65	+0·17	+0·23	+0·10	+0·05	+0·06
Corresponding outflow through doorway (m.³/sec.)	+0·130	+0·055	+0·065	+0·035	+0·020	+0·023
Room temperature (° C.)			Approximately 22·5			
Temperature difference with corridor (° C.)			≯0·4			
Proportion of time room doors were open (%)	56	93	95	100	75	95
Number of movements (per hour) of persons through patient-room doorways, in either direction			Approximately 40			

Table 2. *Room-to-room transfer indices* (log_{10} *median values* +5, *sec./m.³*)

Location of Source Ward	Location of Receiver Ward	Series 1		Series 2	
A	A	0·88	S.D. 1·75	2·96	S.D. 0·94
B	B	2·55		3·39	
C	C	2·71		3·18	
A	B	2·14	S.D. 0·70	1·61	S.D. 1·59
B	A	0·82		2·85	
B	C	1·82		0·85	
C	B	0·62		1·34	
A	C	1·32*		0·30*	
C	A	0·44*		0·64*	
Between single rooms (*a*)		3·24			
(*b*)		2·97			
(*c*)		2·41			

For transfers between the single rooms:
(*a*) for both rooms doors open,
(*b*) for the average situation (doors open 61% of the time),
(*c*) for both doors closed.

* All values between Wards A and C are uncertain owing to the few positive results and the necessary extrapolation, the figures are probably over estimates.

The standard deviations are increased in some cases by the grouping together of measurements with widely differing values, e.g. from transfers in opposite directions along the corridor.

The figures in the table give the median values of the logarithms to the base 10 of the observed transfer indices +5, e.g. the logarithms of the median transfer index from rooms in Ward B to those in Ward A was 0·82−5 = $\bar{5}$·82 and the value of the transfer index was therefore $6·6 \times 10^{-5}$ sec./m.³.

Table 1 gives the average conditions during those periods when air transfer measurements were made. It will be seen that most doors were open most of the time. This was true also of the corridor doors. The only exception was that the patient room doors were shut for about 40% of the time in ward unit A during the first series of measurements.

Room-to-room air transfers

The recorded transfer indices between different room combinations were examined for the different ward-to-ward combinations. Many of the transfer indices were below the limit of measurement by the equipment but in the ward combinations in which there were sufficient measurements the distribution was approximately logarithmic-normal. Thus the log-median of each ward-to-ward combination was found by graphical means by plotting the points on logarithmic-probability paper. It appeared that in either series the standard deviations for the ward-to-same-ward combinations were similar as were the standard deviations for the ward-to-different-ward combinations. An average standard deviation was assumed in each case and used to determine the medians. The assumption of the same standard error allowed the determination of median values for combinations

Table 3. *Ward-to-ward averaged relative source-to-recipient room tracer-gas concentrations*

Room containing source in Ward		Series 1			Series 2			
		A	B	C	A	B	C	
Recipient room in Ward:	A	58,000	58,000	>200,000	520	550	>96,000	A
	B	3,100	1,100	110,000	11,000	150	19,000	B
	C	>21,000	5,800	930	>240,000	55,000	280	C

The method of calculation by which these figures are derived is illustrated by the following example. Consider transfer from a room in Ward B to a room in Ward C during series 1. The average ventilation rate in rooms in Ward B was 6·5/hr. (Table 1) and the average room volume 144 m.^{3}. Hence the transfer index into room B was $3600/(6{\cdot}5 \times 144) = 3{\cdot}85$ sec./m.^{3}. The transfer index to rooms in Ward C (Table 2) was anti log $(1{\cdot}82 - 5)$ or 66×10^{-5} sec./m.^{3}. The ratio of the concentration in the source room in Ward B to that in the receiving room in Ward C was therefore $3{\cdot}85/(66 \times 10^{-5}) = 5800$.

where very few of the observations showed measurable levels of transfer. The estimated log-medians together with the average standard deviations used are given in Table 2.

It is necessary to qualify some of the figures. In both series the values of transfers from Ward A to Ward C and vice versa are probably only upper limits as they were based upon a small number of measurements and a considerable degree of extrapolation. It should be remembered that series 1 had only a selection of rooms in which air samples were taken. In general these rooms were sufficiently representative so that the results may be compared directly with those of series 2 in which all rooms were used. Unfortunately, for structural reasons, both sample rooms in Ward C were situated towards the end of the ward nearer to Ward B; corrections for this would reduce the average values of transfers between Wards A or B and Ward C.

From the figures in Table 2 and from the values of the transfer index to the source room derived from the ventilation rate, transfer index = 1/(ventilation rate × room volume), the relative concentrations of tracer-gas in source and recipient rooms were found. These are given in Table 3.

Comparison of the results from each series shows significant differences. The average reduction in concentration from a source room to another room in the same ward was at least 1000-fold during series 1 when the majority of the rooms had a marked positive pressure and very much greater within Ward A where the pressures were substantial and the doors were closed more often. This fell to between 150 and 500 during the approximately balanced conditions of series 2. In both cases the greater outflow of air from the rooms of Ward A than from the rooms of either of the other two wards was shown to have a significant effect in reducing the transfer of air between the rooms of that ward.

The transfer of air to the rooms of other wards varied considerably but was usually much less than the transfer within a ward except for transfers from rooms

in Ward A during series 1. A significant difference between the series was the predominant direction of air transfer from a ward. In series 1, it is clear that there was a preferred direction of transfer from Ward A to Ward B and, possibly, to Ward C. In contrast series 2 shows that there was a preferred transfer direction from the rooms of Ward C towards Ward B and then to Ward A. This is discussed in more detail below.

Components of air transfer

The above analysis has been carried out on data which were grouped according to the ward units, specifically for the purpose of comparison with bacteriological and clinical data. This will be discussed in a later paper. Such grouping to some extent obscures the patterns of air movement which were observed. A more detailed analysis will now be attempted.

The transfer of air between two rooms can be considered to take place in three stages. There is the transfer from the room into the communicating corridor, there is the transfer along the corridor and finally the transfer into the recipient room. These stages were considered in terms of the relative concentration of a tracer-gas being liberated continuously under equilibrium conditions. If C represents the concentration of tracer-gas and the subscripts S, 1, 2 and R indicate the positions source room, corridor immediately outside source room, corridor immediately outside recipient room and recipient room respectively then

$$\frac{C_S}{C_R} = \frac{C_S}{C_1} \cdot \frac{C_1}{C_2} \cdot \frac{C_2}{C_R}.$$

Values of C_S/C_R are those given in Table 3. Using the notation of Lidwell (1972) this equation may be written:

$$\alpha = \alpha' . \alpha''' . \alpha''.$$

The air transfers between a room and the corridor immediately outside the door, corresponding to the factors α' and α'', and along the corridor, corresponding to the factor α''', were each examined in detail.

Air exchange between a room and the corridor

The movement of air through a doorway has two components. There is a net airflow (F) which is caused by the difference, if any, between the air supplied to and exhausted from the room and there is an exchange airflow (X) which is caused by general turbulence, temperature differences, movement of persons, etc. The magnitude of this is equal in both directions through the doorway. In a room which has a strong positive or negative pressure the net airflow will dominate. In a room which is in balance only the exchange flow will be present. At Greenwich situations existed which ranged from a near balanced system to a moderately pressurized system. Fig. 5 shows a general picture of a room and corridor situation indicating the relevant ventilation parameters. It follows that

$$\alpha' = C_S/C_1 = \frac{V_{ES} + u_S}{u_S} \quad \text{and} \quad \alpha'' = C_2/C_R = \frac{v_{1R} + v_R}{v_R},$$

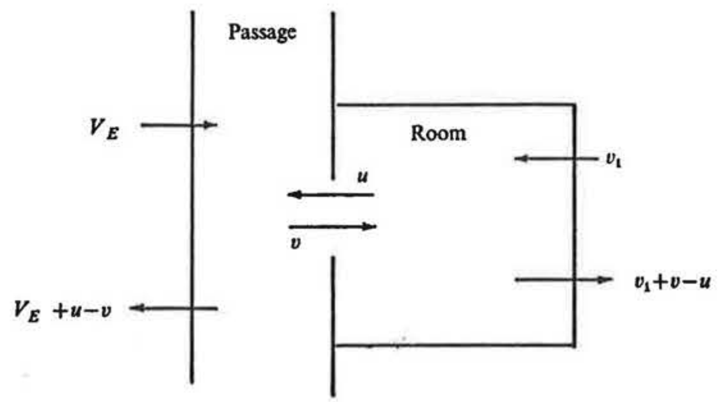

Fig. 5. Generalized plan of a room and adjoining section of corridor showing the variables used in calculating transfer by air movements. V_E, Effective rate of air supply to section of passage immediately outside room door; v_1, rate of supply of ventilating air to room; u, outflow of air from room to passage; v, inflow of air to room from passage. Net airflow through doorway, $F = u \sim v$. Exchange airflow $X = u$ or v whichever is the smaller.

where V_{ES} = effective rate of supply of air to the region of corridor immediately outside the source room door; v_{1R} = rate of supply of ventilating air to the recipient room; u_S = average total outflow of air from source room to corridor ($= F+X$ for positively pressurized room and $= X$ for a balanced or negatively pressurized room); and v_R = average total inflow of air from corridor to recipient room ($= X$ for balanced or positively pressurized and $= F+X$ for negatively pressurized room).

Owing to the difficulty of obtaining representative air samples from any particular part of the corridor it was almost impossible to measure α' and α'' directly. Instead, values of u and v were found which corresponded to different values of F, the excess flow. This allowed the exchange flow X to be calculated.

A tracer-gas was continuously released at a known constant rate within a source room and the situation allowed to reach equilibrium. To measure u, the flow through the doorway and out of each floor-level extract within the room was measured, using the pressure transducer and a direct reading anemometer. The tracer-gas concentration from samples taken at the extracts were also measured. The quantity of tracer-gas passing down the extracts was then calculated, subtracted from the quantity being released and this gave the quantity passing out through the door. Knowledge of the tracer-gas concentration within the room then allowed the gross outflow of air, u, through the doorway to be determined. To measure v, there were two stages. As above, the net flow through the doorway was measured and the concentration of the tracer-gas within the room determined. The extracts were then sealed off in order to create conditions in which all the air entering through the ceiling diffusers left via the doorway. With such a large rate of outflow there was negligible exchange flow. After allowing sufficient time for equilibrium to be established, the outflow through the doorway and the concentration of tracer-gas within the room were again measured. Since the tracer-gas

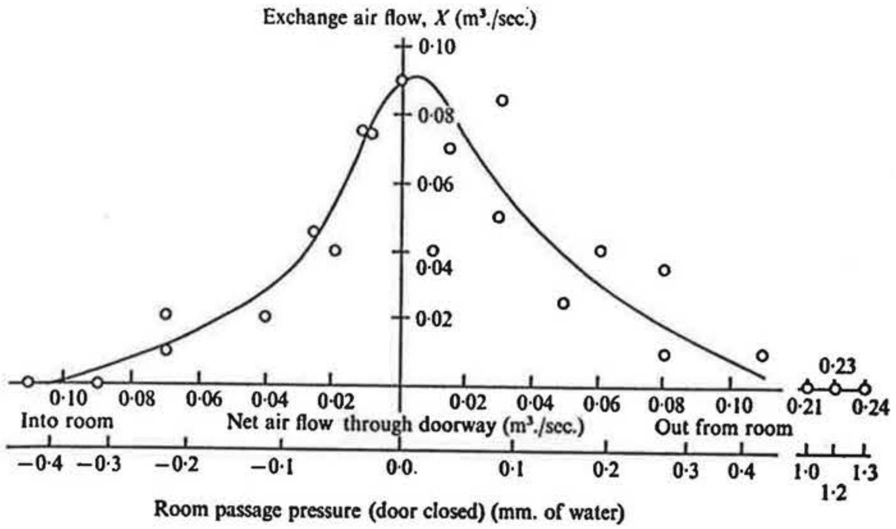

Fig. 6. Exchange airflow through the open doorway of six-bed patient room. The doorway was approximately 1 m. wide × 2 m. high.

concentration is inversely proportional to the total ventilating air entering the room, their ratio under the two conditions gave the ratio of the two ventilating volumes. However, under the latter conditions, the ventilating air was only that from the ceiling diffusers and in the former had the addition of that which entered through the doorway, v, which could therefore be calculated.

Having obtained u and v for a range of values of F, X was calculated in each case and is shown plotted against F in Fig. 6. As would be expected the value of X was at a maximum, about 0·09 m.³/sec., near $F = 0$, i.e. when the room was in balance and was reduced as F increased falling to a very small value when F exceeded 0·1 m.³/sec. Since these results were obtained under the naturally prevailing condition during which both the ventilation and room use fluctuated, with persons entering and leaving the room at random intervals, there was considerable scatter in the results.

It is also important to note that the above values were obtained with minimal temperature differences between room and corridor. The numerical values for the exchange airflow are comparable with those of Whyte & Shaw (1972) at their lowest temperature difference, 0·1° C., although they do not give these explicitly in their paper. That our figures appear to be slightly lower than theirs may be a result of the incomplete mixing within the patient rooms at Greenwich, leading to a zone of lower concentration just within the door of a source room. This would result in a lower estimate of the exchange outflow, assessed from the tracer carried out and the average room concentrations. The data of Whyte & Shaw show the greatly increased values of air exchange to be expected at higher temperature differences. It is likely that there was always a small amount of exchange even when F exceeded 0·1 m.³/sec., caused by the entry and exits of persons, but the method described was not sufficiently sensitive to measure it. The average of 40 exits or entries per hour which was observed would lead to an exchange of approximately 0·005 m.^{3}/sec. if each passage through the door led to an exchange of 0·5 m.^{3} across it (Lidwell, 1972). The value observed here when F exceeded 0·1 m.^{3}/sec. was certainly less than this. The value of 0·5 m.^{3} was derived from observation made when there was little excess airflow through the doorways and it is possible, or likely, that the volume exchanged is much reduced when there is an appreciable flow velocity through the open doorway.

α'' can now be calculated since all the variables are known. The volume of ventilating air within a room calculated from the ventilation rate is the gross value, including that entering through the doorway, i.e. v_1+v. The values calculated agreed reasonably well with those found from the few satisfactory experiments carried out to determine α'' directly.

α' however could not be calculated without a knowledge of V_{ES}, the effective rate of supply of air to the corridor. The few experimental values of α' available suggested that V_{ES} varied in a range from 0·3 to 1·5 m.^{3}/sec.

Air transfer along corridors

Although it was not possible to obtain representative corridor air samples because of unstable and non-uniform flows, it was possible to study the transfer of air along the corridor by looking at the transfer between two rooms and allowing for the effects of transfer between the particular source and recipient rooms and the corridor.

If we put

$$\alpha''' = (V_{E'}+u_S)/(V_{ES}+u_S)$$

then

$$\alpha = \alpha'.\alpha''.\alpha''' = \frac{V_{ES}+u_S}{u_S}\cdot\frac{v_{1R}+v_R}{v_R}\cdot\frac{V_{E'}+u_S}{V_{ES}+u_S} = \frac{V_{E'}+u_S}{u_S}\cdot\frac{v_{1R}+v_R}{v_R}.$$

Values of $V_{E'}$ can then be calculated for transfers from a source room to any recipient room, α, u_S, v_R and v_{1R} being known, and are equivalent to the effective diluting air-supply rate in the whole corridor between source room and recipient room. These values have been plotted graphically, and the results, averaged for each ward unit, are shown in Fig. 7. The lowest values, estimated directly outside a source room, correspond to values of V_{ES} and these lie between 0·25 and 0·60 m.^{3}/sec. Theoretical calculations in a later paper (Lidwell, 1975) lead to estimates of V_{ES} between 0·22 and 0·34 m.^{3}/sec. The two series do not differ greatly although the directions of air movement along the corridors have changed completely. This was probably a consequence of changes in the hospital elsewhere rather than the alterations to the ventilating system in the wards under study. The value of α''' varies between about 3 and a little over 100 per 10 m. of passage length with an average of about 10 (the individual rooms are spaced approximately 6·5 m. apart). The substantial differences between the two series already noted, e.g. in Table 3, derive principally from the room to corridor pressure differences, and the consequent differences in the movements of air between the rooms and the corridors.

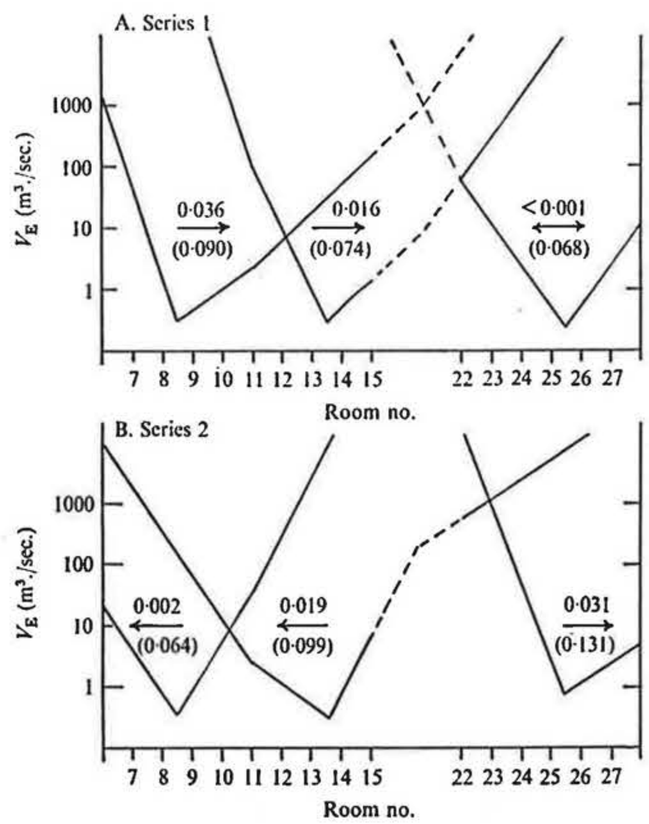

Fig. 7. Dilution of tracer-gas along the ward corridor. (A) Series 1, March–June 1971. (B) series 2, June–August 1973. The arrows show the direction and the figures above the magnitude (in m./sec.) of the drift velocity along that part of the corridor. The figures in brackets below the arrows give the corresponding diffusion constants in m.^{2}/sec. (see Lidwell, 1975). One room spacing was approximately equal to 6·5 m.

CONCLUSIONS

Provided the ventilation conditions are reasonably well known, the above results provide a means of assessing the likely air isolation between two rooms having a communicating corridor. Fig. 8 has been constructed in this way to show the effect of varying the rate of airflow through the doorways. The values used are those found in Greenwich hospital but similar rates of ventilation are likely to be found in other mechanically ventilated buildings. It will be seen that, with open doors, the degree of isolation improves as the airflow through the door increases, reaching a maximum value at net airflows of about 0·1–0·12 m.^{3}/sec. The maximum level reached is slightly higher for inward flow than for outward flow since the effective ventilation in the corridor was greater than that in the patient rooms. Clinical considerations also favour negatively pressurized rooms if, as at Greenwich, the system includes single patient rooms which may be used to isolate infective patients. As the net airflow is increased above 0·1–0·12 m.^{3}/sec. the effectiveness of the isolation appears to decrease slowly. This is a consequence of

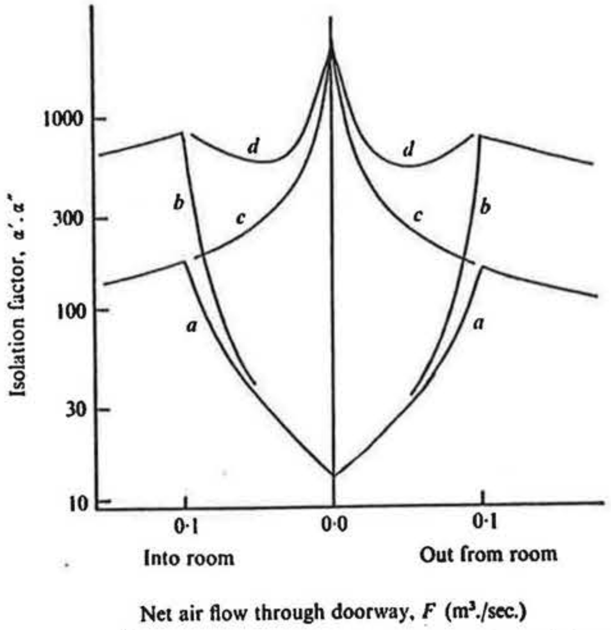

Fig. 8. Relative tracer-gas concentrations in source and receiving rooms opening off the same section of passage.

The vertical scale gives the equilibrium concentrations in the source room divided by that in the receiving room, i.e. $\alpha' \alpha''$. If the rooms are separated by a length of corridor then the values given must be multiplied by the dilution along the corridor, α''', so that $\alpha = \alpha' \alpha'' \alpha'''$.

Curves *aa* have been calculated for open doors with a minimum exchange across the doorway (x), due to movement of persons at 40 movements per hour, of 0·005 m.³/sec.

Curves *bb* have been similarly calculated assuming a minimum exchange of 0·001 m.³/sec.

Curves *cc* are calculated for closed, but leaky, doors with a minimum exchange of 0·005 m.³/sec. and curves *dd* for closed (leaky) doors with a minimum exchange of 0·001 m.³/sec.

The shape of the curves *dd* is dependent on the way in which the exchange flow, X, falls as the excess flow, F, increases. As F tends to zero some exchange may take place through gaps across the doors so that the maximum value of α reached is uncertain and may be less than that shown.

The values are calculated from the formula

$$\alpha' \alpha'' = \frac{(V_{ES}+u_S)(v_{1R}+v_R)}{v_R . u_S}, \text{ see text.}$$

where V_{ES} is taken as 0·3 m.³/soc., v_{1R} as 0·2 m.³/sec., u_S and v_R are deduced from the data of Fig. 6 but assumed not to fall below the minimum values of x given above.

the increased outflow of contamination from the source room while the residual exchange due to passage of personnel in and out of is assumed constant. Although there is evidence to suggest that this exchange may be about 0·5 m.³ for each passage through the doorway when there is only a small net airflow through it the data obtained from the patient rooms at Greenwich suggests that the value is less than this when the airflow velocity through the doorway exceeds 0·05–0·06 m./sec. Two sets of curves are therefore shown in Fig. 8, one for a constant residual exchange of 0·005 m.³/sec., corresponding to an exchange of 0·5 m.³ for each of the 40 entries or exits per hour, and the upper curve for the isolation values resulting if the residual exchange is assumed to fall to 0·001 m.³/sec. at a net flow of 0·1 m.³/sec. If it were to be assumed that it continued to fall beyond this net flow velocity then the degree of isolation might remain constant or even continue to rise at higher net flow velocities.

If patient room doors can be kept closed improved isolation can be obtained, as indicated by curves *c* and *d* in Fig. 8. The gaps around the doors will usually allow any difference between air supply to and extract from the rooms to pass between the room and the passage, so that the improvement is only appreciable if the net flow is small, i.e. less than 0·01–0·02 m.³/sec. Since at these low net flows isolation is poor if the doors are left open and may be much reduced by even small temperature differences, it may be better to compromise at net flow values of 0·1–0·12 m.³/sec. However, if the doors are close fitting and some form of pressure relief openings can be provided in the rooms so that when the doors are closed more of this net flow passes through these openings and no more than 0·01 m.³/sec. passes between a room and the passage then high degrees of isolation can be reliably maintained (Lidwell, 1975).

The corridor also plays a large part in the isolation of rooms. It is easily possible to achieve in a corridor a relative dilution of three-fold for every room space, about 6–7 m., the two rooms are apart, the average value at Greenwich was five-fold, so that the total isolation between the two rooms is multiplied by this factor for each interval.

These figures are derived from a consideration of the median values of the transfer index between rooms. As is clear from the values of the standard deviation given in Table 2 transfer was a very variable process apparently dependent on random events. Transfers on individual occasions might be 100-fold greater than the median values.

The work described above relates only to the transfer of air and tracer-gases (or gaseous contaminants) totally via the air between the rooms of a fully mechanically ventilated building. It shows that a dilution of at least 1000 times between rooms in the same ward and many times this between rooms further apart, is easily possible under suitable ventilation and typical conditions of use. In considering the significance of these figures in relation to the airborne transport of infective material it is necessary to take into account the differences due to the particulate nature of this. These are discussed in detail in the following papers (Foord & Lidwell, 1975; Lidwell, 1975). Particle loss by sedimentation during the process of transport from room to room increases the ratio of source room to recipient room concentrations by between 5 and 20 times according to the distance between the rooms concerned.

Our thanks are due to the Hospital Administration for their willingness to allow us to carry out these studies, to the Hospital Engineer and his staff and to the Engineering Division of the Department of Health and Social Security who helped us with the many technical problems which arose and last but not least, to the

Nursing Staff and the patients of the wards concerned for their cheerful tolerance of our curious antics, which undoubtedly at times caused them some inconvenience.

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Airborne infection in a fully air-conditioned hospital

II. Transfer of airborne particles between rooms resulting from the movement of air from one room to another

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SUMMARY

Experiments were conducted simultaneously with gas and particle tracers to determine the relative loss of particles between source and recipient sites in the hospital ward units. The magnitude of this loss could be accounted for by the assumption of sedimentation from well-mixed air masses during the time required for movement between source and recipient sites. As a consequence of this loss the degree of isolation between patient rooms for airborne particles was between 4 and 25 times greater than that for gaseous contamination, which reflects the actual transport of air between the rooms.

The design and construction of portable spinning-disk particle generators suitable for field studies is discussed.

INTRODUCTION

A technique has been described (Foord & Lidwell, 1972) for measuring the airborne transfer of particles of bacteria-carrying size between sites within a hospital. Potassium iodide particles are produced from a solution using a spinning-disk generator. The number of particles reaching another position are assessed by sampling the air through a membrane filter, developing the collected particles with palladium chloride solution and counting the subsequent, easily observable brown spots. Since it is possible to detect a single potassium iodide particle by this method, it has the maximum possible sensitivity for a particle tracer. We have used this technique to study the extent of particle transfer occurring as a result of the movement of air between rooms in the hospital wards studied in the previous paper (Foord & Lidwell, 1975). We have also designed and constructed spinning-disk particle generators which are more convenient for the purpose than those previously available.

There are many advantages in using a spinning-disk generator for particle production, the most useful, perhaps, being the uniformity of particle size, but high rotational speeds are necessary to produce large numbers of particles with settling rates as low as 5 mm./sec. (1 ft./min.), which is approximately the median value commonly found for airborne bacteria-carrying particles (Noble, Lidwell & Kingston, 1963).

APPARATUS

Design of a conveniently portable spinning-disk generator

The earliest spinning-disk generators employed air-driven rotors (e.g. May, 1949) of around 2·5 cm. diameter driven at speeds up to 60,000 rev./min. It is not always easy to maintain stable operation of these and the associated equipment for the compressed air supply is heavy and bulky and often noisy.

Electric motor drive affords the possibility of a simpler device if sufficiently high speed motors are available. Lippmann & Albert (1967) describe an instrument using a motor designed for operation on a 400 Hz supply at 24,000 rev./min. which could be run up 60,000 rev./min. by raising the supply frequency to 1000 Hz. An apparatus of this type is made by the Environmental Research Corporation, Minneapolis, Minnesota, U.S.A., but is very noisy, inefficient at generating particles with equivalent particle diameters above 5 μm. and the motor bearings have a relatively short life.

Walton & Prewett (1949) proposed the following formula for the primary droplet size produced by a spinning-disk:

$$\delta = K\sqrt{\frac{T}{\omega^2 \rho D}},$$

where δ = droplet diameter, T = surface tension of the liquid, ω = rotational speed, ρ = liquid density, D = disk diameter, and K is a 'constant'. Since the final airborne particle of potassium iodide is produced by evaporation of a solution of this salt the dry particle diameter is given by

$$d = 0{\cdot}215\,\sqrt[3]{(a/\rho')}\,.\,\delta,$$

where a is the weight percentage of the salt in the solution and the density of the dry particle is ρ'. A settling velocity of about 5 mm./sec. corresponds to a diameter of about 7 μm. for a particle of potassium iodide, which has a density of about 3 g./cm.^{3}.

By increasing the disk diameter and by the use of 80 % alcohol as a solvent, which has a lower surface tension than water, it is possible to reduce the rotational speed required for the production of primary droplets of a suitable size. It was also found experimentally that the value of K diminished as the rotational speed was reduced. This made possible the use of rotational speeds as low as 24,000 rev./min.

Mains driven spinning-disk generator

The design of this generator was along similar lines to that referred to above. A cross-section of the apparatus is shown in Fig. 1. The disk was 30 mm. diameter and made from stainless steel. It was driven by an a.c. synchronous motor (Globe Industries Inc., type FC) run from a 110 V. variable-frequency power supply. The speed of the disk was usually 45,000 rev./min., for which a power-supply frequency of 800 Hz was required. A blower provided an airflow of about 500 l./min. to disperse the particles. It also drew a small bleed of air from the vicinity of the disk through the motor housing. This enabled the small satellite particles formed to be

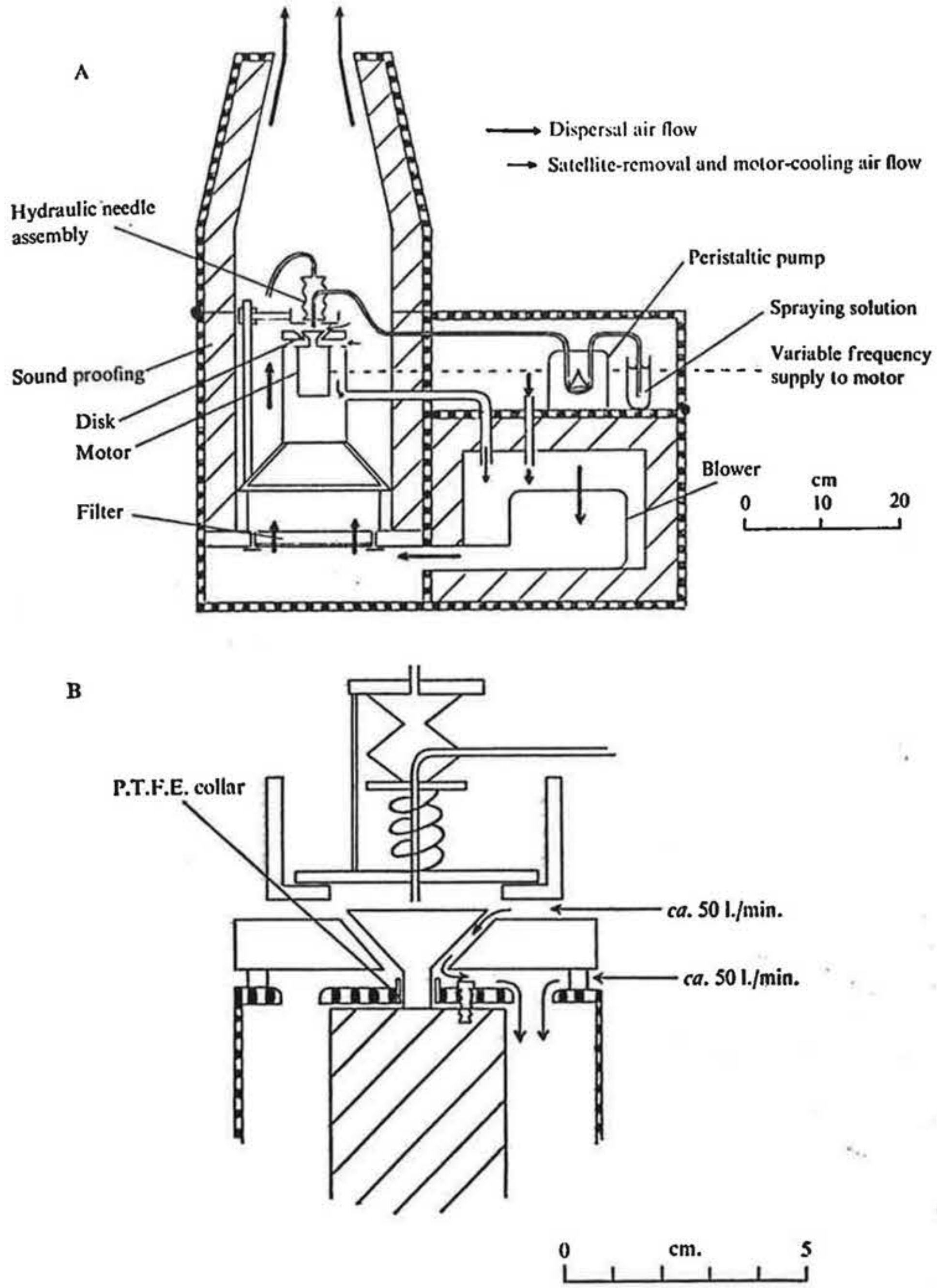

Fig. 1. Sectional view of the mains driven spinning-disk airborne-particle generator. (A) General view. (B) Detail of spinning-disk assembly.

removed, as their inertia was insufficient to carry them beyond the effect of this small bleed into the dispersion airstream as in the case of the larger particles. This air bleed also provided cooling for the motor, but care had to be taken to ensure that the flow was as low as possible to reduce the risk of particles or liquid entering the motor bearings. A collar, made from PTFE (polytetrafluoroethylene) and fitting round the motor shaft, also helped to prevent the entry of corrosive material. Considerable sound proofing was included in the design. The solution was fed by a peristaltic pump at 1 ml./min. from a needle, the height of which above the disk was adjusted hydraulically. The primary droplet produced was about 32 μm. diameter and by using a 4% solution of potassium iodide in 80% alcohol a particle of about 7 μm. diameter was produced. This apparatus performed consistently and satisfactorily; its main disadvantage was the large size. Together with its trolley and mains-driven variable-frequency generator, it stood about 1·5 m. high, 0·7 m. wide and 0·4 m. deep and weighed 40 kg.

Battery driven spinning-disk generator

At the expense of some of the refinements of the mains-operated model, a fully portable instrument which measured no more than 25 × 25 × 30 cm. high and weighed less than 2·5 kg., including five U2 batteries, was constructed. A diagram of this apparatus is shown in Fig. 2. The disk was enlarged to 36 mm. diameter and made from aluminium coated Melinex about 0·1 mm. thick to reduce weight. It was driven by a nominal 2 V. d.c. motor overrun at 4·5 V. at a speed of about 25,000 rev./min. (Portescap Escap 15 type 050/110). Although there was an air-circulating fan to disperse the generated particles, there was no provision for the removal of the satellite particles. This was satisfactory for our purposes, as suitable collection and detection techniques ensured that the smaller particles did not interfere. No sound insulation was needed as the motor was inherently quiet. The solution was fed at about 0·75 ml./min. through a 0·5 mm. I.D. needle from a syringe with a small controlled air bleed. The syringe was held centrally above the disk by an adjustable clamp. The use of a battery-fed d.c. motor meant that the disk speed was slightly variable and the primary droplet diameter might vary between 40 and 50 μm. This required solutions of between 1 and 2% potassium iodide in 80% alcohol to produce particles with settling rates about 5 mm./sec. (1 ft./min.).

An even simpler version of this generator (Fig. 2B) was made by dispensing with the air-distribution fan. This left an extremely small and compact apparatus. However, in order to avoid loss of particles by local sedimentation it was necessary either to hold it high above any horizontal surface so that the particles mixed with the air before settling out or to provide an external fan or to place it in a moving air stream. The last is often conveniently available near an air-supply inlet in an artificially ventilated building.

Performance of the particle generators

Results with both generators showed that it was easier than suggested by the formula of Walton & Prewett (1949) to reduce the disk speed and still produce

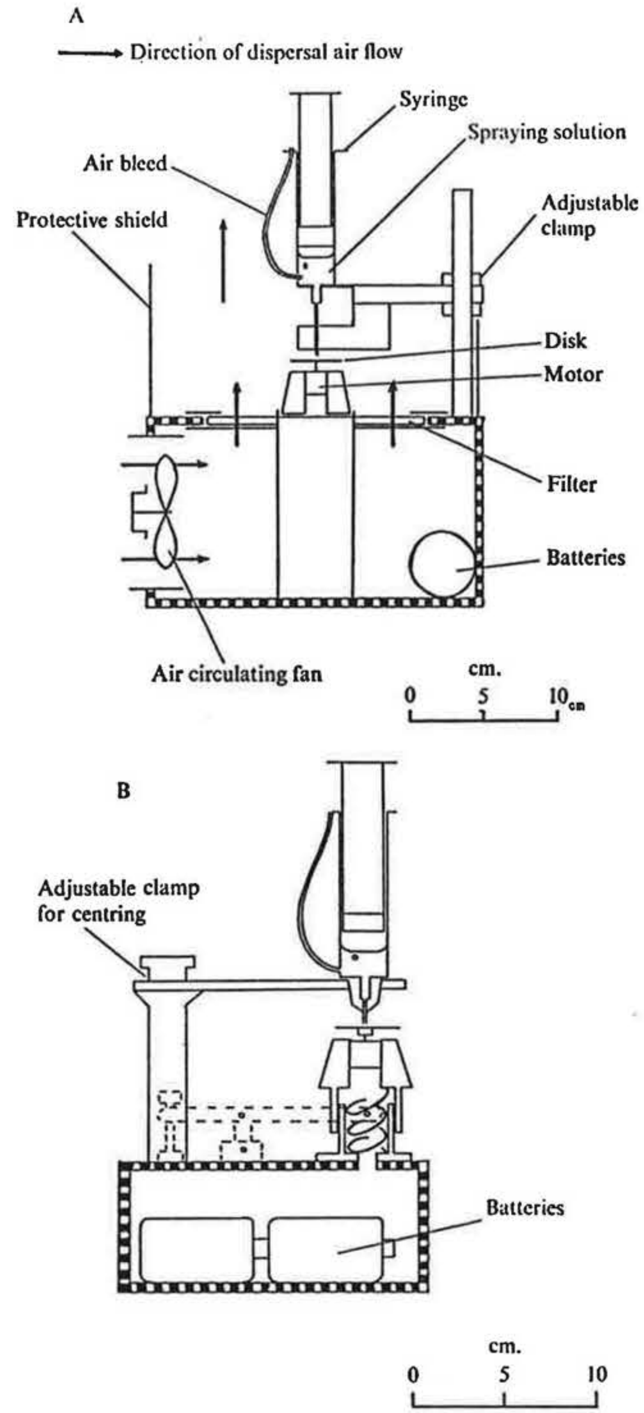

Fig. 2. Sectional views of battery-operated spinning-disk airborne-particle generators. (A) With fan to disperse the particles produced. (B) Simpler design without fan.

Table 1. *Observed values of K for three different spinning-disk generators running at different speeds and spraying absolute or 80 % alcohol at between 0·75 and 1 ml./min.*

Generator	Disk speed (rev./min.)	Disk diameter (cm.)	Primary droplet diameter (μm.)	K	Concentration of† potassium iodide solution (%)	Particles generated/ min.
Envirco*	60,000	2·5	28	5·4	5	*ca.* 1×10^7
Mains driven	45,000	3·0	32	4·9	4	$7·1 \times 10^7$
Battery operated	24,000	3·6	41	3·8	1·5	$2·7 \times 10^7$

* The 'Envirco' generator was that used by Hambraeus & Sanderson (1972). K was calculated from the formula of Walton and Prewett given in the text, taking the density of absolute alcohol as 0·8 g./cm.^{3} and the surface tension as 22 dyne/cm.

† Concentration required to generate particles with a settling velocity in still air of about 5 mm./sec.

particles of the required size. Provided that the slightly greater dispersion in size of the generated particles and the additional satellite particles could be tolerated, the battery-operated model was ideal for use in the field. The noise, even without sound-proofing, was perfectly acceptable. However, it was only after extensive field use in conjunction with gas tracers, that it was possible to determine the efficiency of the generators. This was the number of particles actually generated compared with the total possible number calculated from the amount of solution supplied. In the case of the mains-operated model, about 75 % of the material sprayed eventually formed 7 μm. diameter potassium-iodide particles whereas with the simplest battery-operated model, this figure might be as low as 40 % unless carefully placed in a suitable air stream.

The discrepancy between our results and the formula for primary droplet size is a consequence of variation in the 'constant' K with disk speed as well as with the liquid used. The variation is such that it partly nullifies the consequences of the reduction of speed. A comparison of values of K determined for the above two generators and for the commercial generator used by Hambraeus & Sanderson (1972) in a similar manner but running at a speed of 60,000 rev./min. is given in Table 1.

This variation in K has not been fully explained. Walton & Prewett (1949) give extensive data for a wide range of liquids sprayed from a disk whose speed was varied over two ranges from 300 to 6,000 rev./min. and from 18,000 to 100,000 rev./min. It was noted that the average value of K for the former group was 3·3 whilst that for the latter was 4·5. Using a suitable model of drop formation from a disk, a value between 3 and 4 may be deduced, suggesting that Walton & Prewett's formula fails at high speeds. A possible reason may be that the liquid is unable to acquire the full rotational speed of the disk at high speeds and this leads to the increase in the effective value of K. The speed at which this breakdown occurs probably depends upon the liquid sprayed and its rate of feed on to the disk.

Although it was possible to take advantage of this phenomenon to reduce the disk speed necessary to produce primary droplets of less than 45 μm. from 80 % alcohol without correspondingly increasing the disk diameter, the effect may not extend below 20,000 rev./min. At this speed K is probably approaching its minimum and constant value. There is nothing to indicate what might be its maximum value.

METHODS

The transfer of airborne particles relative to the transfer of air

The technique referred to above using the electrically driven spinning-disk generator was used to study the transfer of airborne particles in the occupied hospital. Air transfer measurements were made simultaneously using the tracer-gas techniques described in the preceding paper (Foord & Lidwell, 1975).

The most important way in which the transfer of airborne particles differs from the transfer of air is the settling of particles on surfaces under the influence of gravity and, if there is no resuspension and if the air is well mixed, this difference will be a function of the time taken for transfer (called here transit time). The relation between the transfer index (as defined by Lidwell, 1960) for a particle tracer compared with that for a gas tracer, would then be of the form:

$$\text{Transfer Index (particle)} = e^{-ST}.\text{Transfer Index (gas)},$$

where S is an effective ventilation rate due solely to particle sedimentation and T is the transit time.

The effective ventilation rate S, under these conditions, should be equal to s/h, where s is the settling rate of the particles in question and h is the height of the area concerned. The purpose of these experiments was to measure simultaneously the transfer index between a source and a recipient position with both particle and gas tracers and to compare the transfer of particles relative to that of the gas tracer in relation to the transit time.

Experiments in the hospital

A suitable source room was chosen and one or, more usually, two recipient rooms or other positions. A particle generator and a gas-tracer disperser were placed in the source room as close together as possible. Liberation of potassium iodide particles and of halogenated hydrocarbon tracer-gas was carried out simultaneously at constant rates, which in the case of the gas tracer was known. The total liberation time was usually 10 min.

At representative positions in the source room and the recipient room or at any other recipient position, integrating particle samplers and gas samplers were placed which operated throughout the liberation of tracer material and for the following 50 min., approximately. This time was long enough to ensure sampling of all tracer reaching the sampling positions. There were usually eight particle samplers in the source room placed either on the floor or on other suitable surfaces. These consisted of 2·5 cm. diameter Millipore filters in suitable holders and particles were collected solely by sedimentation. In recipient rooms there were usually two particle samplers and, necessarily, only one at a particular recipient position. These consisted of centripetal samplers which had an effective sampling rate of 0·00167 m.^{3}/sec. (100 l./min.) and again collected particles on to 2·5 cm. diameter Millipore filters (Foord & Lidwell, 1972). As close as possible to each of the particle samplers was placed a gas sampler. This consisted of a glass syringe barrel which collected an air sample by the displacement of water with which it was filled. The needle through which the water escaped was of such a size that the maximum sampling time was approximately one hour (Foord & Lidwell, 1975).

After the liberation of tracer material and the full sampling period, the samplers were removed for analysis. The filters from the particle samplers were each developed in palladium chloride solution and the brown spots counted to determine the number of particles collected. From each of the collected air samples, a sample was taken and analysed by the gas chromatographic/electron-capture-detector gas analyser and the concentration of the tracer-gas in each was found.

The particle and gas transfer indices were then computed as follows:

$$\text{Transfer Index, by definition, } = \frac{1}{q}\int_0^\infty C.dt,$$

where q is the quantity of tracer material liberated, C is the concentration of tracer material at the recipient position at time t.

The transfer index measured by the gas tracer then becomes:

$$\text{T.I.}_{\text{gas}} = \frac{\bar{C}t}{q},$$

where $\bar{C}$ is the tracer-gas concentration of the integrated sample collected at the recipient position, t is the length of sampling period, q is the volume of gas liberated.

The transfer index for the particles is given by:

$$\text{T.I.}_{\text{particle}} = \frac{n}{Z.N},$$

where n is the number of particles collected at the recipient position, Z is the sampling rate and N is the total number of particles generated.

Since the efficiency of the generator varied, N could not be found directly but had to be deduced from the results of the samples collected within the source room.

The concentration of particles in the air of a room after generation had ceased diminished exponentially with a decay constant given by

$$k = R + s/h,$$

where R is the ventilation rate of the room height, h, and the particle settling rate is s. k was estimated by taking a series of samples in sequence. R was measured by following the decay of the gas-tracer concentration and, by subtracting this from k, s/h and hence s were determined. If n' is the number of particles settling per unit area of room then

$$N = \frac{n'}{s}(v' + sF),$$

Table 2. *Constants of the system used to determine particle transfer indices*

	Mains driven	Battery operated
Room height, h (m.)	2·75	2·75
Floor area, F (m.^{2})*	47	47
$k - R = s/h$ (hr^{-1})	7·5	9·4
s (mm./sec.)	5·7	7·2
sF (m.^{3}/sec.)	0·27	0·34

The battery-operated generator was used in the majority of the experiments.
* Actual 52 m.^{2}, 10 % deducted to allow for poor mixing near walls and door.

where v' is the total volumetric rate of air supply to the room and F its floor area.

The determination of s for the particles used in this investigation is given in Table 2. On all but two occasions the battery-operated generator was used giving particles whose settling velocity averaged around 7 mm./sec. This is slightly, but not significantly, greater than the value of 5 mm./sec. (1 ft./min.) quoted above as the median value for airborne bacteria carrying particles (Noble *et al.* 1963). Values of n' and v' were determined on each occasion, the latter from the gas concentration found in the integrated gas samples and the volume of tracer-gas liberated, i.e.

$$v' = \frac{q}{\bar{C}'t},$$

where the symbols used are as above and $\bar{C}'$ is the tracer-gas concentration of the integrated sample collected within the source room. v' is, of course, numerically equal to the reciprocal of the transfer index from the source to the sampling point in the source room.

Usually, the eight samples within the source room were averaged to find the best estimate for the total output from the particle generator. If a recipient room contained two recipient positions these were averaged and a single value obtained for the transfer index between the source and any recipient room or position.

The particle-to-gas transfer index ratio was the transfer index found using a particle tracer divided by that found using a gas tracer.

To measure the time of transit only the gas tracer was used. At the recipient position, a series of air samples were taken manually with a glass syringe at intervals during the liberation and subsequent sampling period. These samples were then analysed and the concentration of tracer-gas in each was determined. These concentrations were plotted against time and a continuous curve representing the tracer-gas concentration was drawn. From this, the time at which the cumulative time integrated concentration reached half its total was found graphically, t_{50}, and this was taken as the transit time. The mid point of the dispersal period was taken as the time zero.

RESULTS

The results are shown in Fig. 3 where the transit times of 30 transfer combinations are plotted against the corresponding values of the particle-to-gas

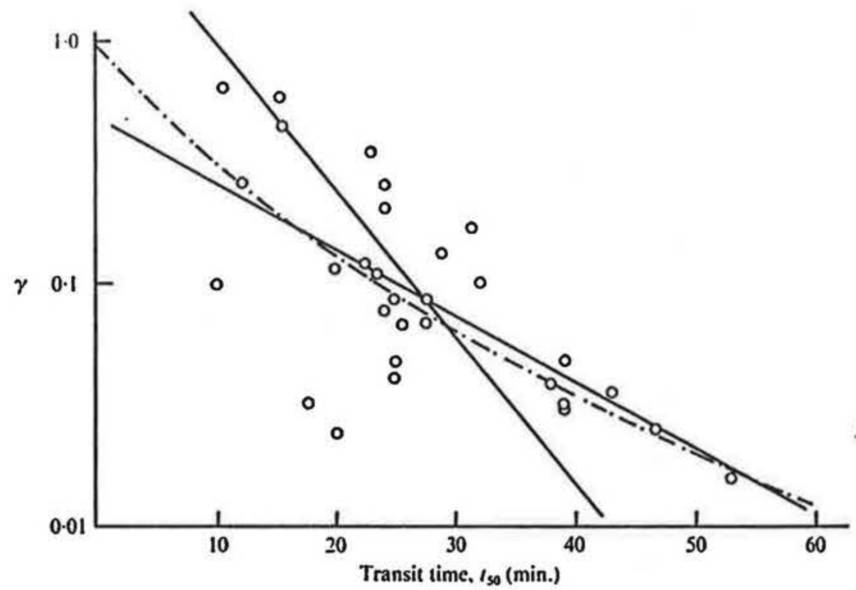

Fig. 3. The particle/gas transfer index ratio, γ, as a function of the transit time between source and receiving site. The transit time is taken from the middle of the period of dispersion up to the time when one half of the material eventually transferred, t_{50}, has reached the receiving site. The full lines show the two regression lines, the correlation coefficient is $-0{\cdot}67$ which corresponds to a probability of less than 0·001, the interrupted line is the best fitting theoretical curve, see text.

transfer index ratio, γ. Transit times were found within the range from 10 to 55 minutes and all the transfer index ratios were less than 100 %. The linear correlation coefficient between the transit times and the logarithms of the transfer index ratios is $-0{\cdot}67$, which is significant to beyond the 0·1 % level.

The simple model proposed earlier for the relation between transit time and the ratio of the transfer indices assumes a single value for the transit time but, as is clear from the method described above for estimating this, both gas and particles reach the recipient room over a considerable period of time and the extent of sedimentation will have varied correspondingly.

In general,

$$\gamma = \text{T.I.}_{\text{particle}}/\text{T.I.}_{\text{gas}} = \int_0^\infty C.e^{-St}.dt \Big/ \int_0^\infty C.dt.$$

A simple function which can be used to approximate to the distribution of arrival times for the gas tracer is

$$C = bt^n.e^{-at},$$

where n, a and b are constants. The equation is then easily integrated to give

$$\gamma = \frac{a^{n+1}}{(a+S)^{n+1}}$$

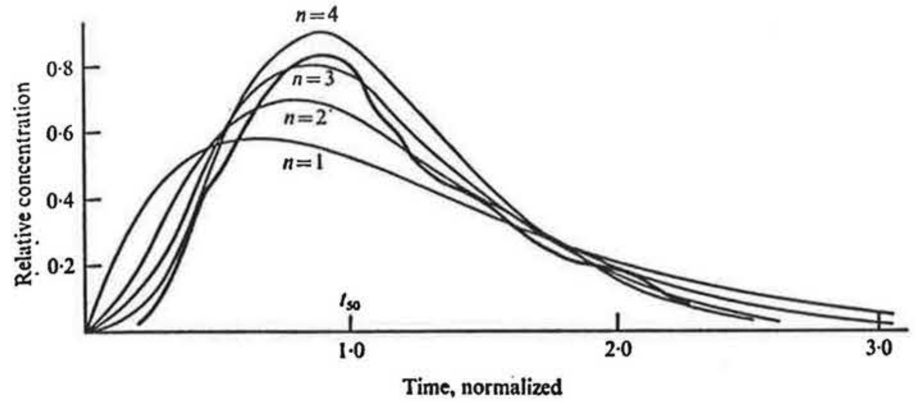

Fig. 4. Concentration time curves for transfer of gas tracer from source to recipient site. All the curves have been normalized to the same total area above the base-line and to make the time for transfer of one half of the material, t_{50}, equal to unity. The family of curves with n = 1, 2, 3 or 4 are derived from the function $C = bt^ne^{-at}$, where a and b are constants and C is the concentration reached at the receiving site after time t. The heavy curve shows an experimental result.

with a time to the maximum value of C, $t_{max} = n/a$ and a time to the 50 % transfer point, t_{50}, approximately equal to $(n+0{\cdot}6)/a$. Hence

$$\gamma \doteq (n+0{\cdot}6)^{n+1}/(n+0{\cdot}6+St_{50})^{n+1}. \quad (1)$$

The values of γ derived from this equation do not differ greatly from those calculated from the simple form $\gamma = e^{-St_{50}}$, if S in this equation is taken as $0{\cdot}7\ s/h$, so long as γ is greater than about 0·025 and n lies between 2 and 4.

Fig. 4 shows the function $t^n.e^{-at}$ together with a typical plot of the gas concentration reaching a recipient room. This it will be seen does not differ greatly from the curve for n = 3. It will also be seen from the curve drawn in on Fig. 3 that the relation between γ and t_{50} is reasonably well represented by the curve

$$\gamma = \left\{\frac{3{\cdot}6}{3{\cdot}6+7{\cdot}1\,t_{50}}\right\}^4,$$

with t_{50} expressed in hours (see equation (1) above).

The value of S of 7·1/hr. in this expression, calculated to give the best approximation to the experimental data, corresponds to a particle settling velocity of $7{\cdot}1\times 2{\cdot}75/3{\cdot}6 = 5{\cdot}4$ mm./sec. which is close to the experimentally determined settling velocities of 5·7 or 7·4 mm./sec. Although there is no reason for the algebraic form of the function employed above, the solutions are very insensitive to the precise function assumed so long as these follow the general shape of an initial delayed rise in concentration followed by an approximately logarithmic decay. The results therefore confirm a relation between the ratio of the particle and gas transfer indices and the transit time which is in conformity with loss of particles by settling in a well mixed system during transport from source room to the receiving site.

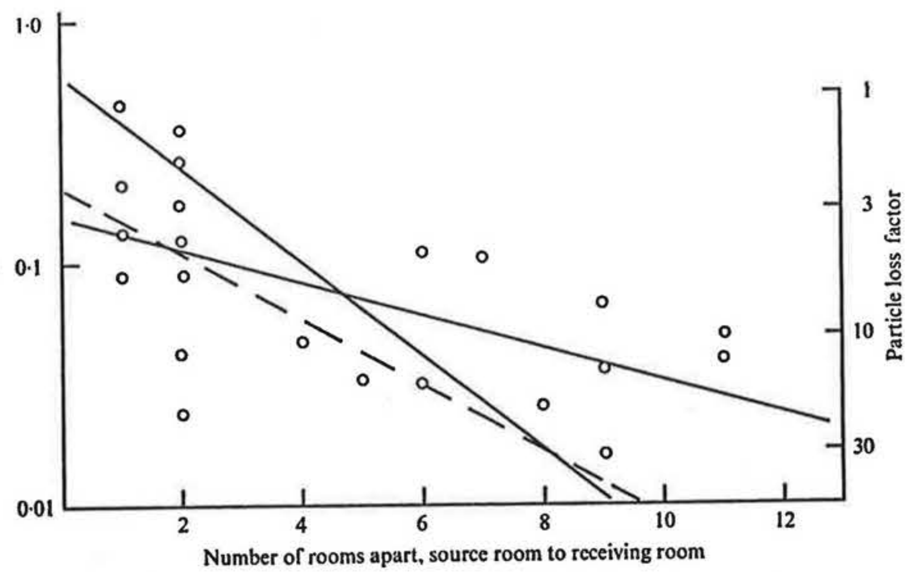

Fig. 5. The particle/gas transfer index ratio, γ, and the particle loss factor, as a function of the distance between source and receiving rooms. The full lines show the two regression lines, the correlation coefficient is $-0{\cdot}59$ which corresponds to a probability of less than 0·003. The broken line is calculated from the ventilation data by the method described in the following paper (Lidwell, 1975).

The points in Fig. 3 show considerable scatter. Some of this can be accounted for by errors in the method. It was impossible to liberate the particles and tracer-gas at exactly the same position and it was not easy to ensure identical liberation periods. The mixing of the tracer materials with the air of the room was not perfect or even the same for the two tracers. Positioning of the samplers within the source room was not always as representative as could have been desired and occasionally a sampler had to be omitted for various reasons. The total sampling period for all the samples could not always be made identical. There were also the usual statistical errors associated with random sampling of discrete numbers of particles.

However, although these factors will have accounted for some of the variation it does not seem likely that they account for all of it. There are a variety of varying processes which may also have contributed. Impaction may have occurred from turbulent air movements. Resuspension of particles can be brought about by activity and was shown to occur during bedmaking. The most probable variable factor, however, was the irregular movement of the air masses as a result of human activity and external wind pressures. It is encouraging that the average effect of all the variables was such that the simple model proposed gives an adequate overall quantitative picture.

Transport of airborne particles between rooms

The experiments described above also gave some direct estimates of the fraction of particles transported by air movement from the source rooms to other

Table 3. *Ward to ward averaged relative source to recipient particle concentrations*

Ward unit				Particle conc. ratio	
Source room	Receiving room	Average spacing (rooms)	Particle loss factor	Series 1 ($\times 10^3$)	Series 2 ($\times 10^3$)
A	A	2·0	4·5	260	2·3
B	B	1·7	4·0	4·4	0·6
C	C	2·3	5·0	4·6	1·4
A	B	4·5	6·3	19·5	69·3
B	A	4·5	6·3	365	3·5
B	C	8·0	11·2	> 65	616
C	B	8·0	11·2	1200	213
A	C	12·5	22·4	> 470	> 5000
C	A	12·5	22·4	> 4500	> 2000

The particle loss factor is defined in the text. The spacing between rooms was approximately 6·5 m.

rooms in the wards studied. The number of these observations however was too few to provide an overall evaluation similar to that given in the preceding paper for gas-tracer transport. In addition to their limited numbers the observations were not representative of the possible room to room transfers.

There was, however, a reasonably good correlation between the ratio of the particle and gas transfer indices, γ, and the separation between the source and receiving rooms. The data are shown in this way in Fig. 5. The points show a similar degree of scatter to those showing the relation between γ and the transit time in Fig. 3 and the correlation coefficient is $-0{\cdot}59$, which is significant to beyond the 0·3 % level. By allowing for the ratio of the transfer indices of particles and gas into the source room, comparisons may be made between the transfer of particles and gas expressed as the concentrations of these in source and receiving rooms.

$$\gamma = \frac{\text{T.I.}_{\text{particle}}}{\text{T.I.}_{\text{gas}}} = \left\{\frac{\text{T.I.}_{\text{particle}}}{\text{T.I.}_{\text{gas}}}\right\}_{\text{source room}} \times \frac{(C_R/C_S)_{\text{particle}}}{(C_R/C_S)_{\text{gas}}},$$

where C is the concentration and the suffixes R and S refer to receiving and source room respectively.

A scale of $(C_R/C_S)_{\text{gas}}/(C_R/C_S)_{\text{particle}}$ which may conveniently be called the particle loss factor is given in Fig. 5.

From the regression line for particle loss factor on room separation, values of the particle loss factor corresponding to the average separation between rooms in the different ward units have been deduced and are given in Table 3. These vary between about 4 and 5 for rooms in the same ward unit to over 20 for rooms in the most widely separated ward units. Combining these with the values for the source/recipient gas concentrations given in Table 3 of the preceding paper (Foord & Lidwell, 1975) leads to the values shown for the source/recipient particle concentration ratios in Table 3.

DISCUSSION

The loss of particles relative to the volumes of air transferred between rooms appears to conform reasonably well with the simple picture of loss by sedimentation from relatively well mixed air masses during the time required for the transport. The effect of this on particle transfer relative to gas transport is substantial and still further increases, for airborne particles which approximate in settling velocity to the median size for airborne particles carrying bacteria, the already high level of isolation between rooms found for gaseous contamination and confirms in this respect the preliminary report of Lidwell & Brock (1973).

Our thanks are again due to the Hospital Administration for their willingness to allow us to carry out these studies, to the Hospital Engineer and his staff and to the Engineering Division of the Department of Health and Social Security who helped us with the many technical problems which arose and last but not least to the Nursing Staff and the patients of the wards concerned for their cheerful tolerance.

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Airborne infection in a fully air-conditioned hospital

III. Transport of gaseous and airborne particulate material along ventilated passageways

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SUMMARY

A mathematical model is described for the transport of gaseous or airborne particulate material between rooms along ventilated passageways.

Experimental observations in three hospitals lead to a value of about 0·06 m.^{2}/sec. for the effective diffusion constant in air without any systematic directional flow. The 'constant' appears to increase if there is any directional flow along the passage, reaching about 0·12 m.^{2}/sec. at a flow velocity of 0·04 m./sec.

Together with previously published methods the present formulae make it possible to calculate the expected average amounts of gaseous or particulate material that will be transported from room to room in ventilated buildings in which the ventilation and exchange airflows can be calculated.

The actual amounts transported in occupied buildings, however, vary greatly from time to time.

INTRODUCTION

A model for assessing the behaviour of an isolation unit comprising a series of rooms opening off a common space has been described previously (Lidwell, 1972). This model was based on the assumption of effectively complete mixing of the air in the several rooms and in the common space with which they communicated. Although this model gave a reasonably good account of the performance of a small burns unit with six patient rooms (Hambraeus & Sanderson, 1972) it was clear that, even in the comparatively short length of the passage way concerned, about 32 m., there were large differences in concentration at different distances from the source of airborne particles entering it. The ward corridor in the part of the hospital studied in the preceding papers was about 100 m. long and any assumption of uniform mixing would clearly have been absurd. A mathematical treatment of diffusion along a ventilated passageway has therefore been developed and applied to this and other situations. Diffusion in this context is transport by any process which follows the diffusion law, that the rate of transport, whether of gas or some property of the medium, across a surface is proportional to the gradient at that point.

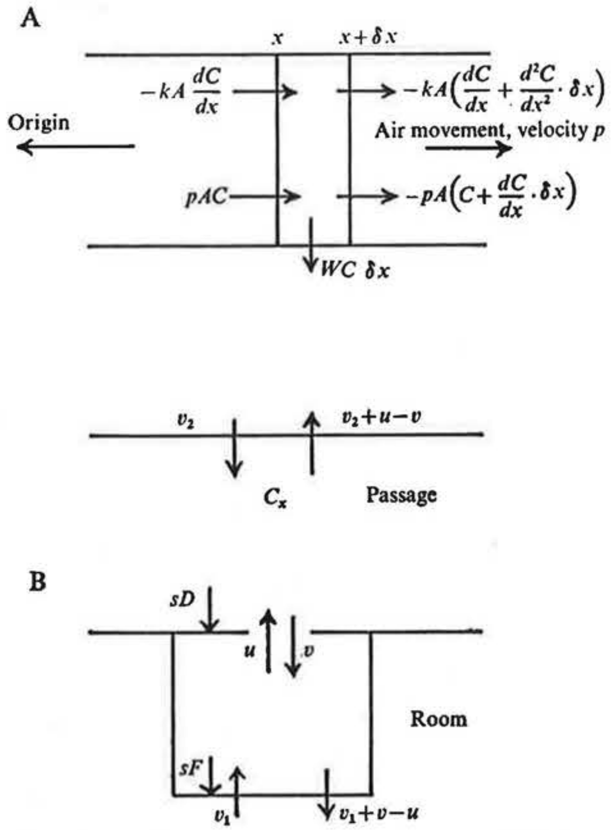

Fig. 1. Calculation of transfer of a tracer along a passage. (A) The quantities of material entering and leaving a thin transverse element situated at distance x from the origin. (B) Exchange with a room which communicates with the passage. The symbols are defined in the text.

AIRBORNE TRANSPORT ALONG A VENTILATED PASSAGEWAY

The model assumed is pictured in Fig. 1. By considering the gain and loss of material for a section of passage of length δx we obtain at equilibrium the following identity:

$$-kA\frac{dC}{dx}+pAC = -kA\left(\frac{dC}{dx}+\frac{d^2C}{dx^2}\cdot\delta x\right)+pA\left(C+\frac{dC}{dx}\cdot\delta x\right)+WC\delta x,$$

whence
$$-kA\frac{d^2C}{dx^2}+pA\frac{dC}{dx}+WC = 0,$$

or
$$\frac{d^2C}{dx^2}-\frac{p}{k}\cdot\frac{dC}{dx} = \frac{W}{kA}\cdot C, \qquad (1)$$

where C is the concentration at distance x from the source (considered as a thin plane across the passageway), A is the cross-sectional area of passage, k is the

diffusion constant and p represents a uniform movement of the air along the passageway. The lateral loss from the passage, per unit length, W is made up of:

(1) Ventilation into the passage, v_2, where v_2 is the rate of ventilation to the passage per unit length.

(2) Sedimentation (of particles) onto the floor of the passage, sD, where s is the velocity of sedimentation of the particles and D is the width of the passage.

(3) Loss due to exchange of air with rooms along the corridor, u', where

$$u' = u-\frac{uv}{v_1+sF+v},$$

summed over all the rooms opening onto the passageway and expressed per unit length of passage, where u = the rate of airflow out from a room into the passage, v the rate of airflow into the room from the passage, v_1, is the rate of air supply to the room and F its floor area.

Hence

$$W = v_2+sD+u-\frac{uv}{v_1+sF+v} \qquad (2)^*$$

(expressed per unit length of passage).

The solution of equation (1) is of the form

$$C/C_0 = K_1e^{m_1x}+K_2e^{m_2x}, \qquad (3)$$

where C_0 is the value of C at the origin, K_1 and K_2 are constants and

$$m_1 = \sqrt{\left(\frac{W}{kA}+\frac{p^2}{4k^2}\right)}+\frac{p}{2k} \qquad (3A)$$

and
$$m_2 = -\sqrt{\left(\frac{W}{kA}+\frac{p^2}{4k^2}\right)}+\frac{p}{2k}. \qquad (3B)$$

Since $C/C_0 = 1$ when $x = 0$, $K_1+K_2 = 1$.

* By considering the model as depicted in Fig. 1B then, for the passage,

$$WC_x = C_x(v_2+u-v)-C_Ru+C_xsD+C_xv$$
$$= C_x(v_2+u+sD)-C_Ru$$

and for the room

$$vC_x = C_R(v_1+v-u)+C_Ru+C_RsF$$
$$= C_R(v_1+v+sF),$$

where C_R is the concentration in the room.

whence
$$WC_x = C_x(v_2+u+sD)-\frac{uv}{v_1+v+sF}.C_x$$

or
$$W = v_2+sD+u-\frac{uv}{v_1+v+sF}.$$

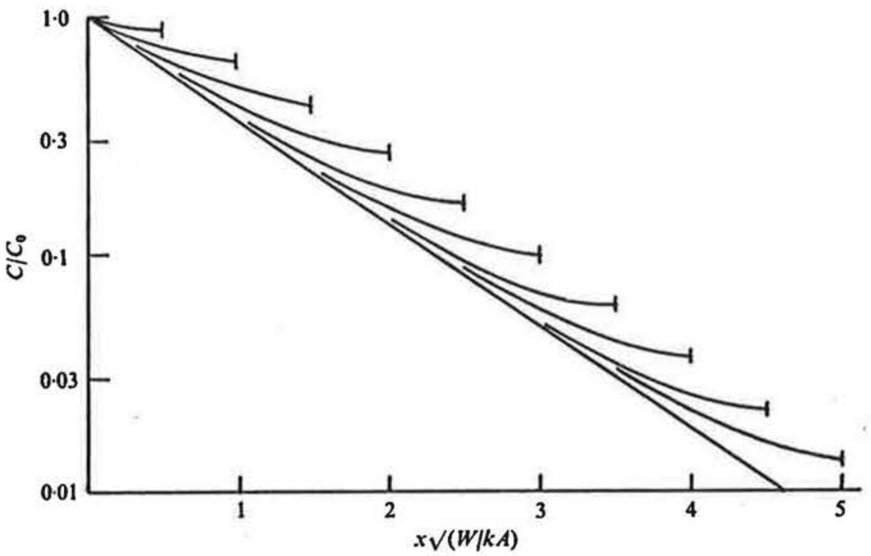

Fig. 2. The concentration gradient produced along passages of finite length closed at the end. The curves are derived from equations (3) and (5) in the text. The underlying straight line from which the individual curves deviate as the ends of the respective passages are approached corresponds to $C/C_0 = e^{-x\sqrt{(W/kA)}}$ (see text).

LONG PASSAGEWAYS

For a passage of infinite length (and uniform conditions)

$$C \to 0 \quad \text{as} \quad x \to \infty$$

and we have

$$K_1 = 0, \quad K_2 = 1.$$

Hence

$$C/C_0 = \exp\left(-\sqrt{\left(\frac{W}{kA}+\frac{p^2}{4k^2}\right)}+\frac{p}{2k}\right). \tag{4}$$

SHORT PASSAGEWAYS

If the passage in one direction from the origin is of finite length, a, then equating the quantity entering this to that lost gives the identity

$$-kA\left(\frac{dC}{dx}\right)_{x=0} = \int_0^a WC.dx.$$

Equation (3) then leads to the relation

$$-kA(m_1K_1+m_2K_2) = W[K_1e^{m_1x}/m_1+K_2e^{m_2x}/m_2]_0^a.$$

Since there can be no uniform movement of air along a passage with a closed end $p = 0$ and

$$m_1 = \sqrt{\left(\frac{W}{kA}\right)}, \quad m_2 = -\sqrt{\left(\frac{W}{kA}\right)}.$$

Hence

$$-\sqrt{(WkA)}(K_1-K_2) = \sqrt{(WkA)}(K_1e^{a\sqrt{(W/kA)}}-K_2e^{-a\sqrt{(W/kA)}}) - \sqrt{(WkA)}(K_1-K_2)$$

and

$$K_1e^{a\sqrt{(W/kA)}} = K_2e^{-a\sqrt{(W/kA)}}, \tag{5}$$

while, as before,

$$K_1+K_2 = 1.$$

In Fig. 2, C/C_0 is shown as a function of $x\sqrt{(W/kA)}$ for various values of $a\sqrt{(W/kA)}$. It can be seen from this figure that C/C_0 departs substantially from $e^{-x\sqrt{(W/kA)}}$ only at distances less than $\sqrt{(W/kA)}$ from the end of the passage and that for values of $a > 1{\cdot}5\sqrt{(kA/W)}$ the terminal value of

$$C \simeq 2C_0e^{-a\sqrt{(W/kA)}}.$$

CONCENTRATION AT THE ORIGIN

For purposes of calculation the material entering the passage from the source room is assumed to be evenly distributed over a plane section of the passage at the origin, $x = 0$. The amount moving in the downwind direction is then

$$-kA\left(\frac{dC_a}{dx}\right)_{x=0}+pAC_0$$

and the amount moving in the upwind direction is

$$-kA\left(\frac{dC_b}{dx}\right)_{x=0}-pAC_0,$$

where C_a is the concentration in the downwind direction and C_b that in the upwind direction.

Equating these to the amount of material entering the passage

$$u_SC_S-v_SC_0 = -C_0kA\{(m_1K_1+m_2'K_2)_a+(m_1K_1+m_2K_2)_b\},$$

where u_S is the rate of airflow out from the source room into the passage, v_S the rate of airflow into that room from the passage and C_S in the concentration in the source room. Hence

$$\frac{C_S}{C_0} = -\frac{kA}{u_S}\left\{(m_1K_1+m_2K_2)_a+(m_1K_1+m_2K_2)_b+\frac{v_S}{kA}\right\}$$

If the passage is long in both directions $K_2 = 1$, $K_1 = 0$ and from equations 3A and 3B

$$(m_2)_a = -\sqrt{\left(\frac{W}{kA}+\frac{p^2}{4k^2}\right)}+\frac{p}{2k}, \quad (m_2)_b = -\sqrt{\left(\frac{W}{kA}+\frac{p^2}{4k^2}\right)}-\frac{p}{2k}$$

and

$$\frac{C_S}{C_0} = \frac{2kA}{u_S}\left\{\sqrt{\left(\frac{W}{kA}+\frac{p^2}{4k^2}\right)}+\frac{v_S}{2kA}\right\}. \tag{6}$$

Table 1. *Transport of airborne particles along the passage in a burns unit*

Distance from source room, x (in m.)	C/C_0	$a\sqrt{(W/kA)}$	$\sqrt{(W/kA)}$
−10	Entry end	—	—
−7·5	0·221	2·4	0·24
0	(1·00)	—	—
+7·5	0·089	7·0	0·32
+15·0	0·055	4·25	0·19
+22	Inner end		

The values of $a\sqrt{(W/kA)}$ have been estimated from the data given in Fig. 2 by choosing that curve which intersects the given value of C/C_0 at the appropriate value of x/a, where a is the distance from the source room to the end of the passage in the direction concerned.

In a previous paper (Foord & Lidwell, 1975*a*) estimates were made of a notional ventilation rate to the passage, treated as if there were complete mixing within it. On this basis

$$\frac{C_S}{C_0} = \frac{V_{ES}+u_S}{u_S},$$

where V_{ES} is the notional ventilation rate in relation to the part of the passage immediately outside the source room door. Then from equation (6)

$$V_{ES} = 2kA\left\{\sqrt{\left(\frac{W}{kA}+\frac{p^2}{4k^2}\right)}+\frac{v_S}{2kA}\right\}-u_S. \quad (7)$$

COMPARISON WITH OBSERVED DATA

For these calculations the suffixes S and R are used to denote quantities relating to the source and receiving rooms respectively. C_0 is the concentration in the passageway immediately outside the source room and C_x that outside a receiving room at distance x along the passage.

1. *Uppsala burns unit*

The results obtained for transport of airborne particles between the room and along the passage of this unit have been described (Hambraeus & Sanderson, 1972).

From the data given, W can be estimated as the sum of the corridor ventilation and sedimentation (exchange with the rooms was negligible). Hence

$$W = \frac{1100}{2600\times 32}+0{\cdot}005\times 3 = 0{\cdot}025 \text{ m.}^3\text{/sec./m.}$$

The data for the passage concentrations are given in Table 1 from which an average value for $\sqrt{(W/kA)}$ can be estimated as 0·25/m. The cross-sectional area of the passage was approximately 8 m.² and hence

$$k = 0{\cdot}025/(8\times 0{\cdot}25^2) = 0{\cdot}050 \text{ m.}^2\text{/sec.}$$

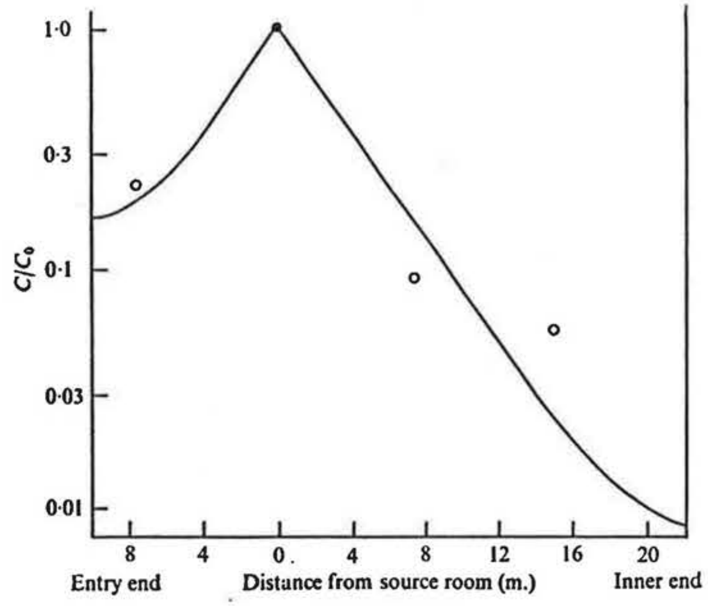

Fig. 3. The variation in concentration of particle tracer along the passage of the Burns Unit at the Uppsala University Hospital (Hambraeus & Sanderson, 1972). The full lines show the calculated curves. The experimentally observed values are indicated by open circles.

From Table 2 in the paper cited

$$u_S = 17/3600 = 0{\cdot}0047 \text{ m.}^3\text{/sec.}$$

As there was no uniform airflow along the passage, which was closed at both ends, $p = 0$ and, since v_s was small, equation (6) leads to

$$\frac{C_S}{C_0} = 2\sqrt{(WkA)}/u_S = 42{\cdot}5.$$

This compares well with the value of 45 given in Table 1 (line 2) of the same paper.

By using equation (5) values for K_1 and K_2 along the passage in both directions can be calculated and the concentration profile along the passage deduced. This is shown in Fig. 3.

2. *Greenwich District Hospital*

Transport of tracer gas

The variations of C/C_0 along the passage in both directions from source rooms in different positions in the ward units studied are shown in fig. 7 of a preceding paper (Foord & Lidwell, 1975*a*). As the passages were relatively long the formula of equation (4) has been used for purposes of computation and the values of $(d \ln C/dx)$ are given in Table 2. From equation (4) it can be immediately seen that the product of the values $(d \ln C/dx)$ in the two directions, i.e. upwind and downwind (p negative and positive respectively), is equal to W/kA. Similarly the difference of these two values is equal to p/k. Values for V_{ES} have then been

Table 2. *Transport of tracer-gas along ward corridor*

Series 1	W (m.³/sec./m.)	u (m.³/sec.)	v (m.³/sec.)	d ln C/dx A → C	d ln C/dx C → A	W/kA (m⁻²)	k (m.²/sec)	p/k (m⁻¹)	p (m./sec.)	V_{ES} (m.³/sec.) calc.	V_{ES} (m.³/sec.) obs.
A	0·0446	0·140	< 0·005	0·52	0·12	0·062	0·090	0·40	0·036	0·33	0·30
B	0·0359	0·100	0·046	0·38	0·16	0·061	0·074	0·22	0·016	0·26	0·30
C	0·0315	0·080	0·070	0·24	0·24	0·058	0·068	0·00	< 0·001	0·25	0·25
Series 2											
A	0·0356	0·092	0·040	0·28	0·25	0·070	0·064	0·03	0·002	0·22	0·36
B	0·0322	0·091	0·057	0·32	0·13	0·042	0·099	0·19	0·019	0·28	0·35
C	0·0316	0·081	0·062	0·092	0·33	0·030	0·131	0·24	0·031	0·34	0·60

The symbols have the meaning given in the text. Values of W were calculated according to equation (2). All values of W, u, v and ($d \ln C/dx$) are averaged for each ward unit. Two values of ($d \ln C/dx$) are given, for transport from end A of the ward area towards end C and vice versa. A = 8 m.². Values of k, p and V_{ES}(calc.) have been obtained as described in the text. The values of V_{ES} (obs.) are derived from the data of Fig. 7 (Foord & Lidwell, 1975*a*).

Table 3. *Calculation of the particle loss factor for transport between rooms in Greenwich District General Hospital*

Quantity	Series 1		Series 2	
u (m.³/sec.)	0·107		0·088	
v (m.³/sec.)	0·039		0·053	
v_1 (m.³/sec.)	0·205		0·195	
p (m./sec.)	0·017		0·017	
k (m.²/sec.)	0·077		0·098	
	Gas	Particle	Gas	Particle
W (m.³/sec./m.)	0·036	0·054	0·033	0·051
$-d \ln C/dx$ (average for two directions)	0·266	0·316	0·223	0·269
d/dx ($\log_{10}\alpha''$)	0·116	0·137	0·097	0·117
α'	3·5	4·1	4·8	5·6
α''	6·2	13·9	4·7	10·3
d/dx ($\log_{10}(\alpha_p'''/\alpha_g''')$)	0·021		0·020	
$\log_{10}(\alpha_p'/\alpha_g')$	0·063		0·067	
$\log_{10}(\alpha_p''/\alpha_g'')$	0·350		0·340	
$\log_{10}$(particle loss factor)/m.	$0·413+0·021x$		$0·407+0·020x$	
$\log_{10}$(particle loss factor)/room interval, $(X) = 6·5$ m.	$0·413+0·130X$		$0·407+0·136X$	

The symbols are defined in the text. Values of u, v, p and k are taken from Table 2 averaged over all the ward units. Values of v_1 are derived similarly from those given in Table 1 of a previous paper (Foord & Lidwell, 1975*a*), by equating $v_1+v(1-1/\alpha')$ to the product of the ventilation rate and the room volume. v_2, the ventilation to the passage, was at the rate of about 0·014 m.³/sec./m. In addition to the exchange of air between patient rooms and the passage, which can be calculated from the values of u and v given above there was also exchange between the passage and the service rooms which opened off it. No measurement of this was obtained but from the number of these rooms and their ventilation arrangements an estimate of 0·008 m.³/sec. per metre of passage length was made and this has been included in u' when calculating the values of W by means of equation (2). $d \ln C/dx$ can then be calculated from equation (4).

$\alpha' = C_S/C_0$ is obtained from equation (6) and $\alpha'' = C_x/C_R$ as given by Fig. 1, i.e. $(v_1+v+sF)/v$. The sedimentation rate for the particles, s, has been taken as 0·006 m./sec., see Foord & Lidwell (1975*b*). D, the width of the passage was 2·8 m., A, its cross-sectional area, 8 m.² and F, the floor area of a patient room, 47 m.², see Foord & Lidwell (1975*b*).

calculated according to equation (7). The results of these calculations together with the appropriate values of W, u and v are given in Table 2.

Comparison of particle and gas transport

In a previous paper (Foord & Lidwell, 1975*b*) the effects of particle loss during transport between rooms in the ward units has been discussed. Good correlation was obtained with the transit time. In addition the particle loss factor was also correlated with the distance apart of the two rooms (fig. 5 in that paper).

The value of W, equation (2), includes a term for loss by sedimentation. It is therefore possible to deduce the difference in transport between gas tracer and particles which would be expected on the basis of the model proposed in this paper. Using the known values of air supply to patient rooms and passage and the previously estimated values for air exchange between these rooms and the passage the concentration gradient along the passage can be calculated from equation (4). The 'particle loss factor' has been defined earlier (Foord & Lidwell, 1975*b*) as

$$(C_S/C_R)_{\text{particle}}/(C_S/C_R)_{\text{gas}} = \alpha_{\text{particle}}/\alpha_{\text{gas}}.$$

This can be broken down into three components

$$\frac{(C_S/C_0)_p}{(C_S/C_0)_g}\cdot\frac{(C_x/C_R)_p}{(C_x/C_R)_g}\cdot\frac{(C_0/C_x)_p}{(C_0/C_x)_g} = \frac{\alpha'_p}{\alpha'_g}\cdot\frac{\alpha''_p}{\alpha''_g}\cdot\frac{\alpha'''_p}{\alpha'''_g}.$$

Equation (4) gives estimates of $d \ln C/dx$ for both gas and particle tracers. The difference between the two values, with change of base, then gives $\log_{10} (\alpha'''_p/\alpha'''_g)$ per unit length of passage. Values of α'_p and α'_g can be obtained from equation (6). The values of α''_p and α''_g follow directly from the relationship shown in Fig. 1 since

$$\alpha'' = C_x/C_R = (v_1+sF+v_R)/v_R.$$

The results of all these computations are given in Table 3 together with the values of the particle loss factor derived from them. The logarithms of these values are shown as a function of the distance along the passage between the rooms or as a function of the number of rooms apart for the Greenwich inter-room spacing of 6·5 m. This is compared with experimental data in fig. 5 of the previous paper (Foord & Lidwell, 1975*b*). It will be seen that the calculated values indicate a somewhat higher particle loss factor than that deduced from the experimental data but the variability in the data is much greater than the discrepancy. On the basis of both the experimental and the calculated results it would seem that a good approximation to the particle loss factor is given by the relation:

$$\text{particle loss factor} = 0{\cdot}30+0{\cdot}11X,$$

where the source and recipient rooms are X rooms apart (1 room interval $\simeq$ 6·5 m.).

3. *Isolation unit St Mary's Hospital*

Some measurements with the particle tracer, not reported elsewhere, were made in the isolation unit described by Williams & Harding (1969). This consisted of two groups of patient rooms, each group opening off a ventilated lobby area, linked by a passage about 45 m. long. There was a perceptible movement of air along the passage from west to east. The width of the passage was 1·8 m. and the ventilation supply small. Hence, $W \simeq 0{\cdot}005\times 1{\cdot}8 = 0{\cdot}009$ m.^{3}/sec./m., being the loss due to sedimentation of the particles.

Measurements of the variation in particle concentration along the passage were made in both directions and led to the following values:

$$\left(\frac{d \ln C}{dx}\right)_{\text{E}\to\text{W}} = 0{\cdot}092, \text{ in the east to west direction,}$$

$$\left(\frac{d \ln C}{dx}\right)_{\text{W}\to\text{E}} = 0{\cdot}253, \text{ in the west to east direction,}$$

hence $W/kA = 0{\cdot}0233$ and $p/k = 0{\cdot}161$.

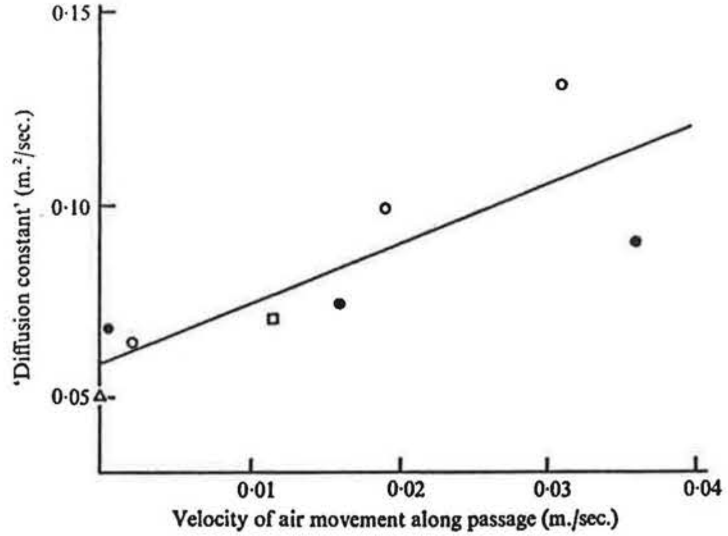

Fig. 4. Values of the diffusion constant in passages in relation to the overall velocity of air movement along the passage. The circles give the values obtained from the obervations made at the Greenwich District General Hospital. Open circles, series 1; filled circles, series 2. The triangle is derived from observations made in the Uppsala Hospital and the square from those made at St Mary's Hospital, London.

Since the cross-sectional area of the passage, A, was 5·5 m.^{2} this gives $k = 0{\cdot}070$ m.^{2}/sec. and $p = 0{\cdot}011$ m./sec.

DISCUSSION

The model proposed is able to give a coherent picture of the transport of both gas and particle tracers along the ward corridor in the Greenwich Hospital. The data from the other two situations are too limited to give any confirmation of the value of the method taken individually. It is, however, worth noting that the air drift velocities deduced are reasonable in magnitude. The highest value is 0·036 m./sec. (approximately 7 ft./min.) which is consistent with the fact that all the air movements were below the velocities measurable by normal anemometry.

The values for the 'diffusion constant' from the several determinations have been plotted together in Fig. 4 against the value of the air-drift velocity. There appears to be a consistent relation between the two quantities, the 'diffusion constant' rising from about 0·06 m.^{2}/sec. in still air to double that value at a drift velocity of about 0·04 m./sec.

Although the consistency of these results is notable it must be emphasized that the variability of the experimental observations from which they have been deduced was very high so that the possible errors of interpretation are considerable. However, taken with the methods developed earlier (Lidwell, 1972) the present work does give a basis for estimating the extent of transport of gases or particles between rooms in ventilated buildings along passage ways of substantial length, e.g. up to 100 m. or more. When or if such calculations are made it must be borne in mind that the actual transfers which take place will almost certainly vary by large factors from time to time. The variations will probably lead to an approximately log-normal distribution of the amount of transferred material with standard deviations up to 2·0 or more (logarithms to base 10). The calculations made here relate only to the median values of such transfers.

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Multiple skin testing in leprosy

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SUMMARY

Groups of patients with lepromatous and tuberculoid leprosy and hospital staff from six leprosaria in East Africa and 'non-contact' groups of villagers or staff from general hospitals have been skin tested with 10 reagents. These were prepared by ultrasonic disintegration from *M. tuberculosis*, *M. duvalii*, *M. chelonei* and 7 other species identified in the Ugandan environment. Comparisons were made of the percentages of positive reactors in each study group for each reagent. The 'specific' defect of lepromatous patients was found to apply to a variable extent to six of the species tested, but not to *M. tuberculosis*, *M. avium* or *M. 'A*'*. The defect applied most noticeably to *M. nonchromogenicum* and *M. vaccae*, suggesting that they are more closely related to *M. leprae* than are the other species tested. The reagent Chelonin produced unexpected and anomalous results in the lepromatous group. It is suggested that this was due to an unusually slow clearing of Arthus' reaction.

INTRODUCTION

It has long been recognized that a deficiency in immunity is associated with lepromatous leprosy and it has more recently been demonstrated that a degree of this deficiency also occurs in tuberculoid patients (Bullock, 1968). Studies on leprosy contacts have shown that the lymphocytes of healthy people may transform markedly in the presence of whole leprosy bacilli (Godal & Negassi, 1973), indicating that subclinical infection occurs and probably conveys some degree of protection. Whether the immune deficit present in the disease is a predisposing factor in its development, or the result of the infection, remains uncertain. It has been suggested that the macrophage of the lepromatous patient is inherently unable to destroy leprosy bacilli (Beiguelman, 1967). Alternatively the apparent macrophage defect may reflect the absence of a circulating clone of thymic (T) lymphocytes reactive to the leprosy organism. In polar cases of lepromatous (LL) leprosy this clone may never have existed; it may have been totally ablated by antigen overload or its activity may have been suppressed perhaps in a manner