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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

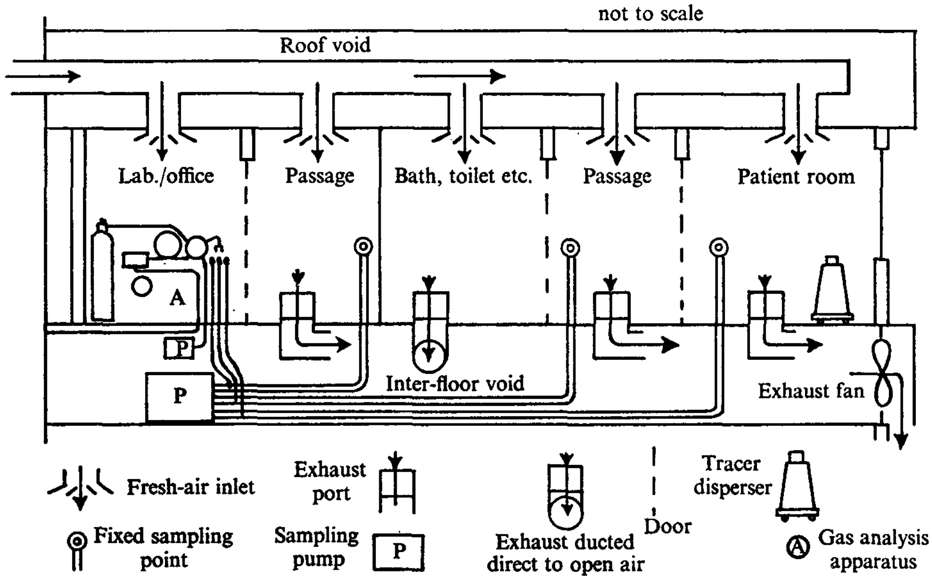

Fig. 1. Section of the medical ward floor showing the ventilation system and the fixed sampling connexions.

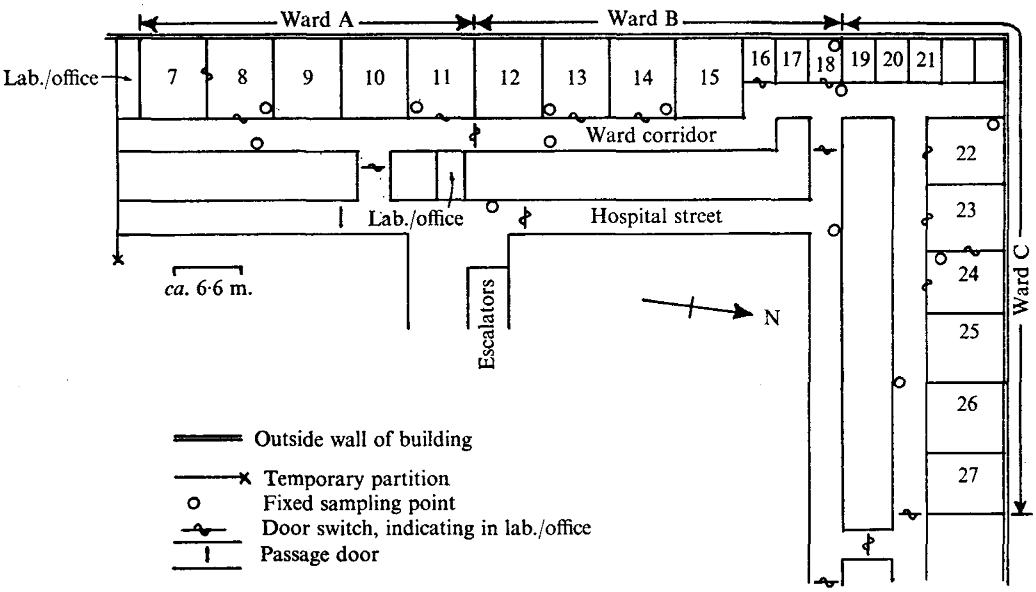

Fig. 2. Plan of part of the medical ward floor showing location of the fixed sampling points and the indicating and recording switches attached to certain doors. Rooms 7–11, 12–15, 22–27 had six beds each, rooms 16–21 were single bed rooms.

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

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* 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

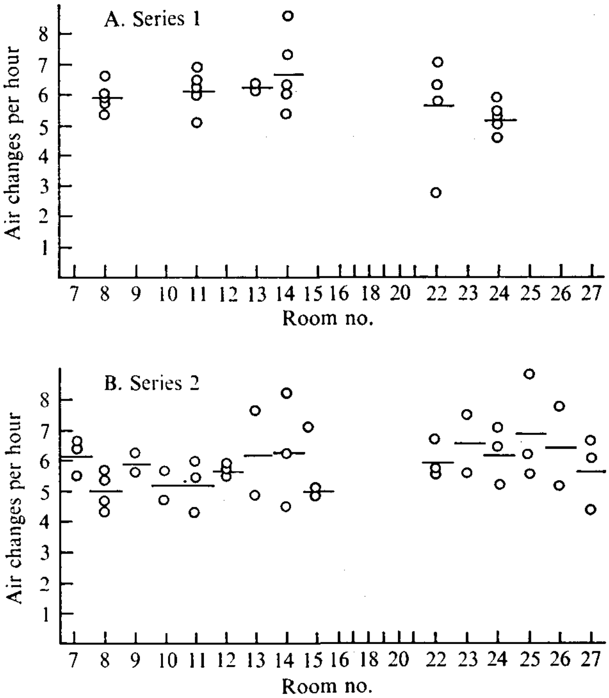

Fig. 3. Observed room ventilation rates. (A) Series 1, March–June 1971. (B) series 2, June–August 1973. The rooms are shown spaced linearly along the horizontal axis. Horizontal bars show mean values for each room.

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.

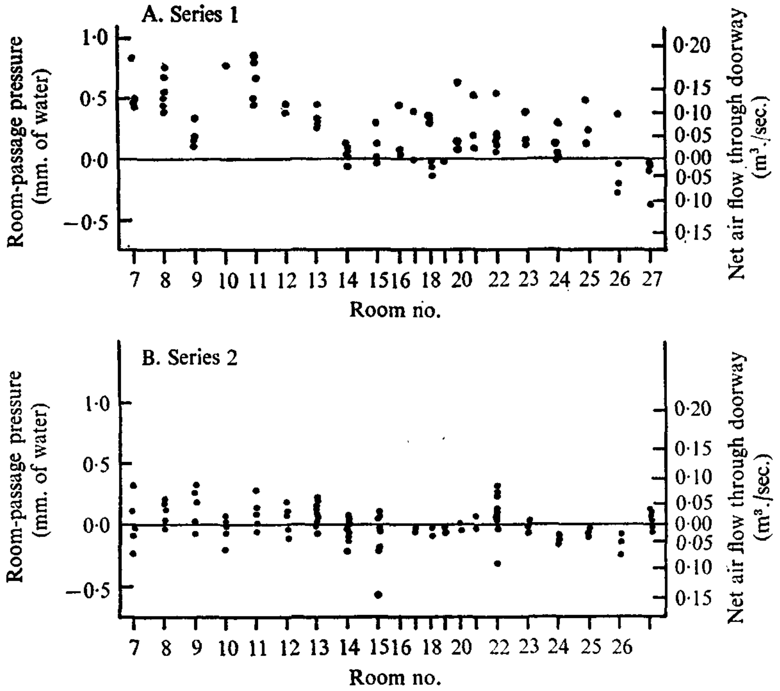

Fig. 4. Room-corridor pressure differences and the corresponding airflows through the doorways. (A) Series 1, March–June 1971. (B) series 2, June–August 1973.

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
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	+0·02
Room temperature (° C.)	Approximately 22·5					
Temperature difference with corridor (° C.)	$\not>$ 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	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 $0\cdot82-5 = \bar{5}\cdot82$ and the value of the transfer index was therefore $6\cdot6\times10^{-5}$ 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

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

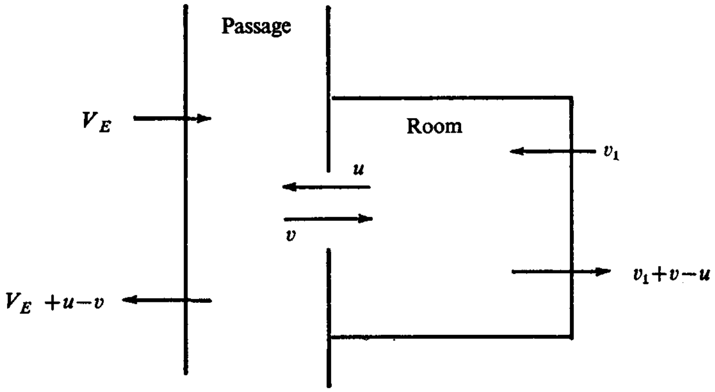

Fig. 5. Generalized plan of a room and adjoining section of corridor showing the variables used in calculating transfer by air movements. V_E, Effective rate of air supply to section of passage immediately outside room door; v_1, rate of supply of ventilating air to room; u, outflow of air from room 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

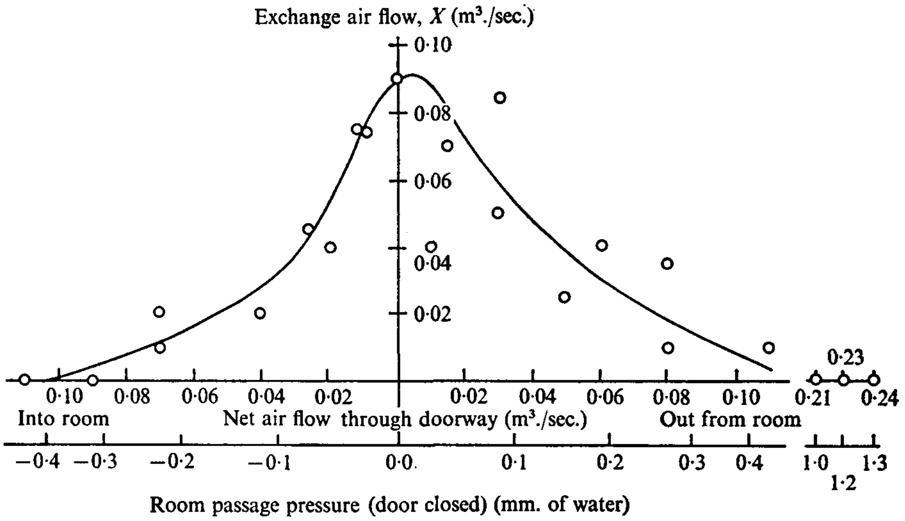

Fig. 6. Exchange airflow through the open doorway of six-bed patient room. The doorway was approximately 1 m. wide × 2 m. high.

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.

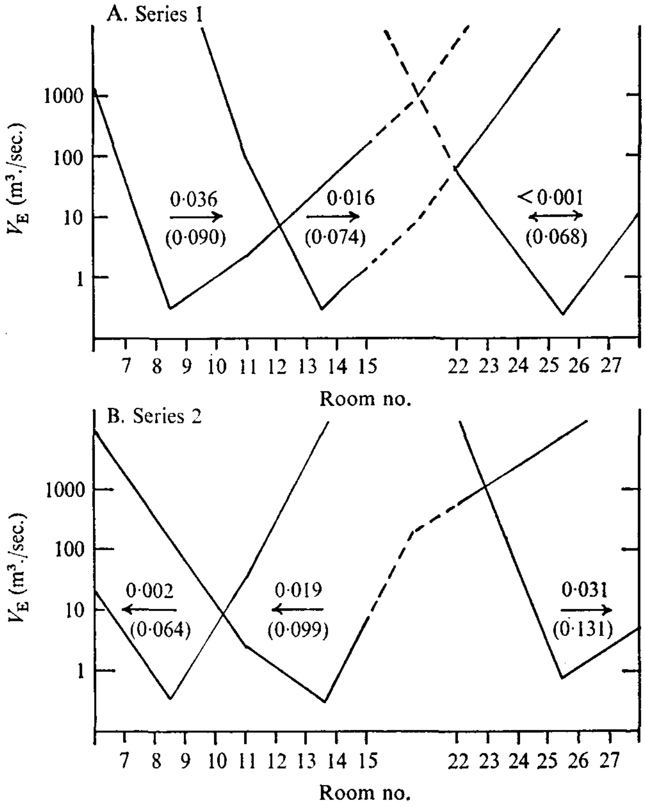

Fig. 7. Dilution of tracer-gas along the ward corridor. (A) Series 1, March–June 1971. (B) series 2, June–August 1973. The arrows show the direction and the figures above the magnitude (in m./sec.) of the drift velocity along that part of the corridor. The figures in brackets below the arrows give the 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

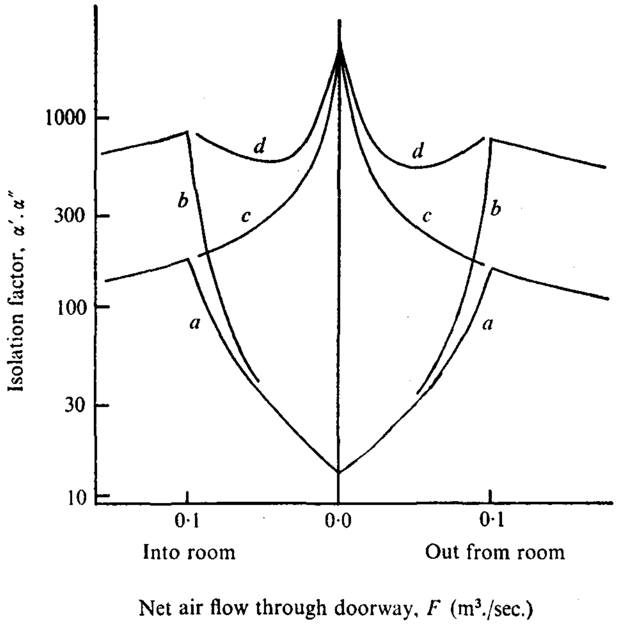

Fig. 8. Relative tracer-gas concentrations in source and receiving rooms opening off the same section of passage.

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}/sec., 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.

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REFERENCES

DRURY, M. & SKEGG, V. E. (1969). The Greenwich District Hospital Scheme. *Journal of the Institution of Heating and Ventilating Engineers* **36**, 359.

FOORD, N. (1973). Ventilation rates and air pressure differences in isolation rooms. In *Airborne Transmission and Airborne Infection* (ed. J. F. Ph. Hers and K. C. Winkler). Utrecht, Netherlands: Oosthoek Publishing Co.

FOORD, N. & LIDWELL, O. M. (1973). A method for studying air movement in complex occupied buildings such as hospitals: halocarbons as gas tracers using gas chromatography. *Building Services Engineer* **41**, 93.

FOORD, N. & LIDWELL, O. M. (1975). 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. *Journal of Hygiene* **75**, 31.

LIDWELL, O. M. (1960). The evaluation of ventilation. *Journal of Hygiene* **58**, 297.

LIDWELL, O. M. (1972). 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. *Journal of Hygiene* **70**, 287.

LIDWELL, O. M. (1975). Airborne infection in a fully air-conditioned hospital. III. Transport of gaseous and airborne particulate material along ventilated passageways. *Journal of Hygiene* **75**, 45.

LIDWELL, O. M. & BROCK, B. (1973). Some aspects of the dispersal of *Staphylococcus aureus* in hospital wards. In *Airborne Transmission and Airborne Infection* (ed. J. F. Ph. Hers and K. C. Winkler). Utrecht, Netherlands: Oosthoek Publishing Co.

WHYTE, W. & SHAW, B. H. (1972). Air movement in isolation and treatment rooms with respect to airflow through doorways. *Building Services Research Unit, Glasgow University, Report No.* 151.