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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

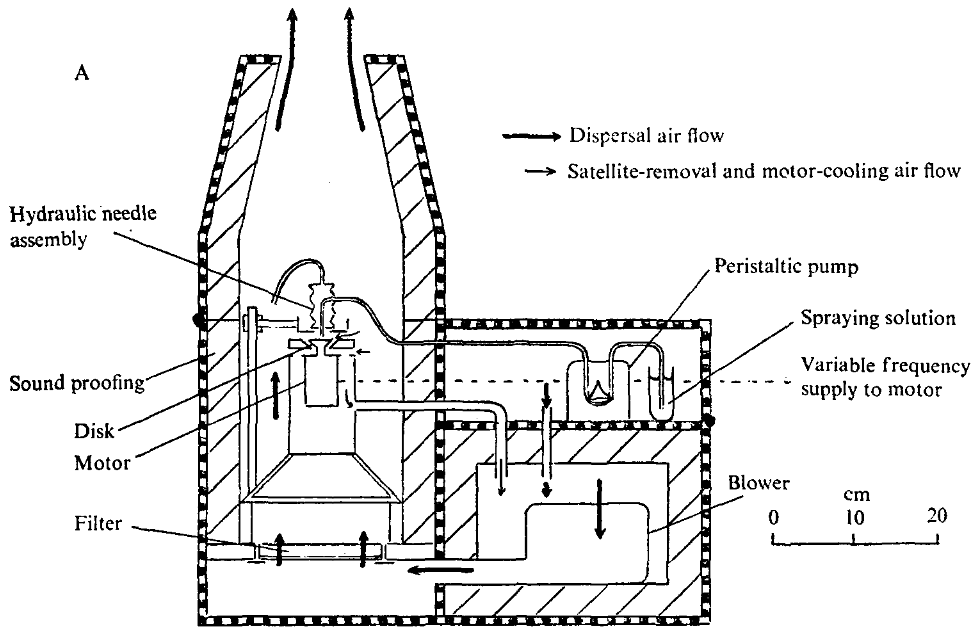
$$d = 0{\cdot}215\sqrt[3]{(a/\rho')}\,.\,\delta,$$

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



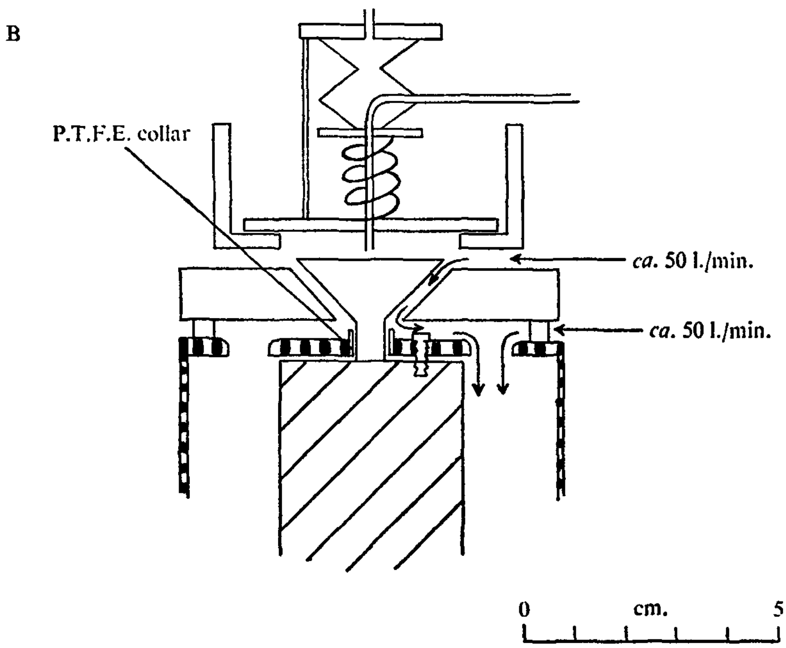


Fig. 1. Sectional view of the mains driven spinning-disk airborne-particle generator. (A) General view. (B) Detail of spinning-disk assembly.

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 $25 \times 25 \times 30$ 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

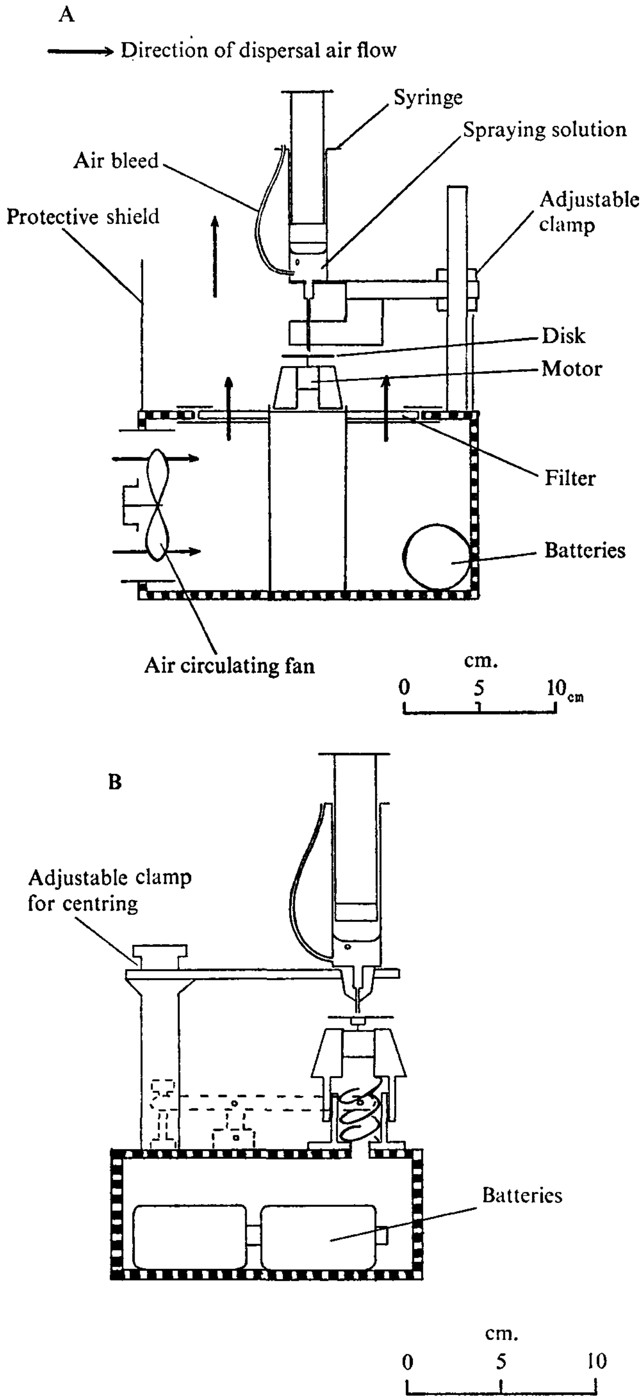


Fig. 2. Sectional views of battery-operated spinning-disk airborne-particle generators. (A) With fan to disperse the particles produced. (B) Simpler design without fan.

Table 1. *Observed values of* K *for three different spinning-disk generators running at differe 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
Mains driven	45,000	3·0	32	4·9	4	7·1 × 10
Battery operated	24,000	3·6	41	3·8	1·5	2·7 × 10

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

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

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

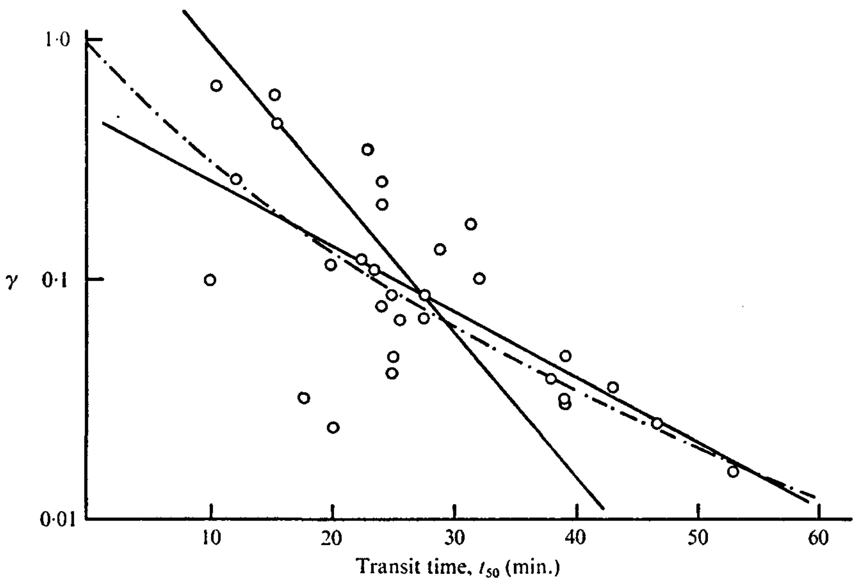


Fig. 3. The particle/gas transfer index ratio, γ, as a function of the transit time between source and receiving site. The transit time is taken from the middle of the period of dispersion up to the time when one half of the material eventually transferred, t_{50}, has reached the receiving site. The 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,

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

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

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

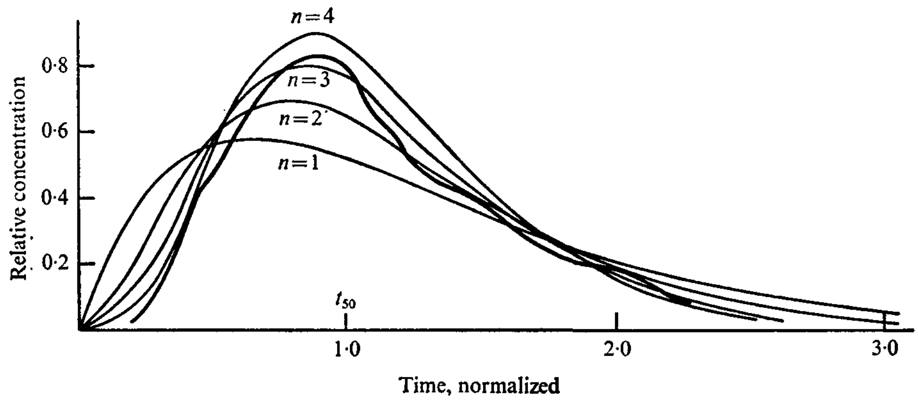


Fig. 4. Concentration time curves for transfer of gas tracer from source to recipient site. All the curves have been normalized to the same total area above the base-line and to make the time for transfer of one half of the material, t_{50}, equal to unity. The family of curves with $n = 1, 2, 3$ or 4 are derived from the function $C = bt^n e^{-at}$, 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

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

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.

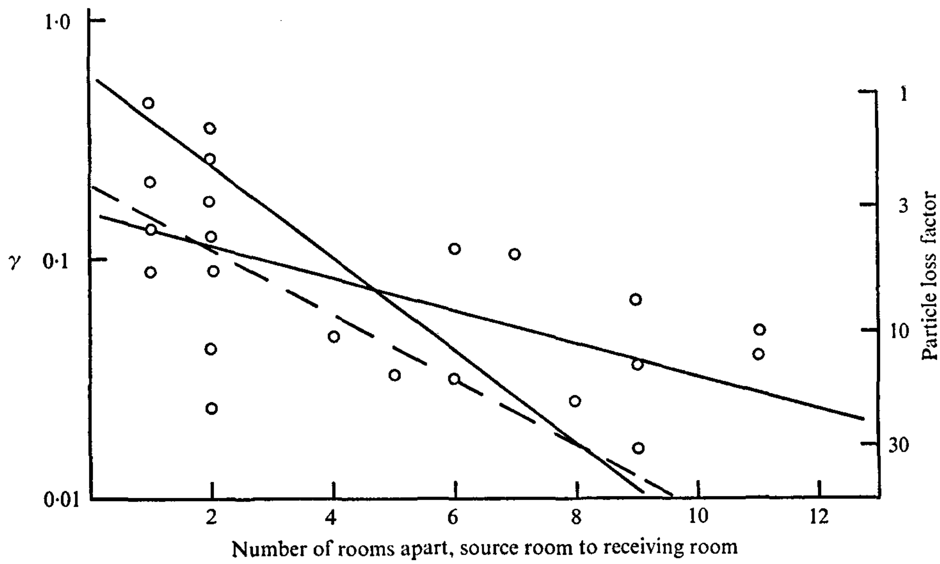


Fig. 5. The particle/gas transfer index ratio, γ, and the particle loss factor, as a function of the distance between source and receiving rooms. The full lines show the two regression lines, the correlation coefficient is $-0{\cdot}59$ which corresponds to a probability of less than 0·003. The broken 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.

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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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