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A comparison between tracer gas and tracer particle techniques in evaluating the efficiency of ventilation in operating theatres

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INTRODUCTION

Operating theatres are ventilated for a number of reasons, one of them being to keep numbers of airborne bacteria low at the operation wound. No matter how air is brought into the room, bacteria are removed by dilution rather than by air currents, because of turbulence caused by heat liberated by people and equipment and by movement in the room (Lidwell & Williams, 1960). With ventilation rates up to 20 air changes/hour, the dilution may differ at different sites in the room depending on the design of its ventilation system.

Tracer gas, smoke, larger tracer particles and aerosolized tracer bacteria have been used to study the efficiency of ventilation (Lidwell, 1960; Foord & Lidwell, 1975; Wiegersma, 1980). As bacteria-carrying particles have a sedimentation rate of approximately 0·3 m/min (Noble, Lidwell & Kingston, 1963), there is some uncertainty as to whether results for gas distribution can be used to predict those of bacteria-carrying particles. The aim of the present investigation was to compare the distribution of gas and particles in an operating room.

MATERIALS AND METHODS

The tracer gas

The tracer gas (N_2O) was released continuously at a constant flow of 130 l/h via a small special point diffuser (diameter 0·03 m). The gas concentration was measured continuously by an infrared analyzer (Miran 101®) and recorded by a printer. Average values were assessed visually from the printed records.

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Smoke

Paraffin oil was evaporated and condensed to particles about 1 μm in diameter in order to create smoke, which was released continuously through the point diffuser to visualize the interaction between air movements and dispersion. To avoid thermal disturbances the smoke was released isothermally. The smoke pattern was recorded by visible light photography.

Air velocities and their fluctuations were also studied with a hot-wire anemometer (Disa®) in the empty room. The values were recorded by a printer. More detailed description of the above-mentioned methods can be found in Ljungqvist (1979).

The particle tracer

A spinning disk particle generator was used to produce an aerosol of potassium iodide particles (Foord & Lidwell, 1975). The sedimentation rate of the particles was determined by measuring the die-away rate in a sealed room as described earlier (Hambraeus & Sanderson, 1972). A concentration of potassium iodide in the solution that gave a particle size with a sedimentation rate of about 0·2 m/min was used.

During four experiments in the sealed room the approximate number of particles generated during an experiment was calculated. This was done by allowing the particles to settle during the entire dispersal period and for 35 min thereafter, which would give time for 90% of the particles to settle. The total number of particles generated per experiment was $1–2 \times 10^8$.

The ventilation system

The operating theatre measured $4{\cdot}7 \times 6{\cdot}8 \times 3{\cdot}2$ m^3. The inlet air was supplied by four diffusers symmetrically placed in the ceiling. Exhaust air was evacuated through four grilles, symmetrically placed on two opposing walls close to the floor. The air volume flow at full speed ventilation was 2250 m^3/h, giving an exchange rate of 22/h.

In one set of experiments full speed ventilation was used, in another the ventilation was reduced to 10 air changes per hour and in another no mechanical ventilation was supplied (0·5 air changes/h measured by tracer gas). All measurements were made under isothermal conditions (20 °C) and a relative humidity varying between 50–75%.

Design of experiments

Gas and particles – sampling sites

Two experimental arrangements were used for both gas and tracer particles, one with the source at the operating table (Q) and one with the source in the periphery (P) (Fig. 1). The source was placed 0·9 m above the floor. Air was sampled on the operating table (D), at one of the exhaust ports 0·15 m above the floor (C), and in two corners of the room at 1 m height (A and B). To confirm that sampling site C was representative for all exhaust ports these were all investigated separately in the empty room.

The duration of each experiment was 35–45 min. In the *gas experiments* continuous measurements were made during the experiment. Two to three

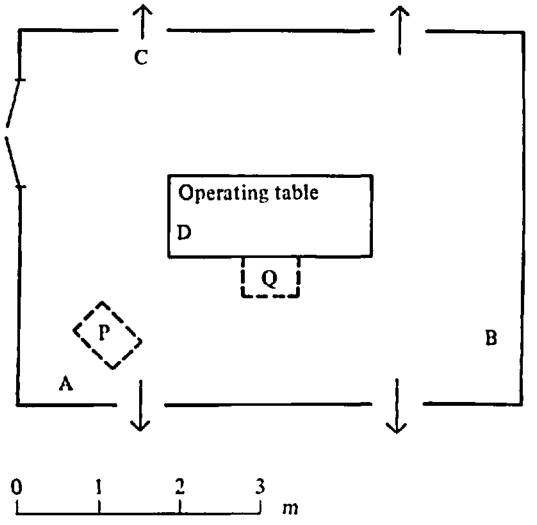

Fig. 1. The positions of sampling points A–D and dispersing source at Q = central and P = peripheral dispersal.

sampling points were measured simultaneously. The experiments were repeated once. *Particle experiments* were repeated four times. In each experiment samples were taken simultaneously in the four points for 30 s during each 5 min period. Calculations were based on measurements during steady state which usually lasted for 30 min.

Activity in the room – empty room

In one series of experiments the room was occupied by only one or two persons operating the gas or particle sampling equipment and moving as little as possible. The operating table was in position, and the unlit lamp pushed to one side and up under the ceiling. During gas experiments the spinning disk was running, as in particle experiments, but without dispersing any particles.

Mock operations

In another series of experiments the activity of a major surgical operation was simulated. The operating lamp was lit and in position over the table. Four additional persons were present, one as a mock patient on the operating table, and three performing a standardized series of movements around the table dressed in caps, masks and operating gowns. Mock operations were not performed without mechanical ventilation.

Bacteria carrying particles

In a separate series of experiments the distribution of bacteria-carrying particles dispersed by people was studied during mock operations performed in full speed ventilation and without mechanical ventilation. In both settings one series was run with the lamp pushed aside and unlit and one with the lamp in position and lit. Each experiment lasted for about 30 min. Bacteria were sampled simultaneously 4 × 5 min on the operating table, under the operating table and in the periphery.

Casella® slit-samplers were used and air was sampled on to blood agar plates. These were incubated aerobically for 2 days at 37 °C and the total number of colony-forming units (c.f.u.)/m^3 was calculated.

RESULTS

Smoke

With the smoke technique it was possible to see that a large amount of air was transported directly from the inlet air diffusers to the exhaust grilles. When smoke was released close to the operation table, the dispersion of smoke had a cloudlike pattern with very high local concentrations as is shown in Fig. 2.

The pattern of dispersion was partly unstable and could change direction. This was studied with the aid of cine-films. With activity in the room there was a better mixing of the air in the operating zone than in the empty room.

Velocity measurements

The mean air velocity at any point was close to zero, but fluctuated violently. At 22 air changes/h the instantaneous values varied up to 0·2 m/s in both directions and at 10 air changes/h up to approximately 0·1 m/s, showing a higher level of turbulence at full than at half speed ventilation.

The influence of dispersal site and the presence of people on the mean levels of gas and particles

The mean gas and particle concentrations obtained for the whole room from the four sampling points are shown in Table 1. With the same ventilation rate the mean concentrations were higher with peripheral dispersal than with central dispersal, except for particles during mock operations at half speed ventilation. The mean particle concentrations during mock operation at full speed ventilation was twice that found in the empty room at the same ventilation rate. The presence of people did not influence the mean gas concentrations.

The distribution of tracer gas in the room

The gas concentrations at different positions and different ventilation rates are given in Fig. 3.

Central dispersal

When gas was dispersed centrally at the operating table, the concentration was lowest at the exhaust port (C), both in the empty and occupied room at full speed ventilation and at zero mechanical ventilation. At half speed ventilation the concentration was lowest in one corner (B), with and without activity.

The highest concentrations were found in A with and without activity at full speed ventilation, in A with and D without activity at half speed ventilation. With no mechanical ventilation the concentrations were above the measuring limit of the equipment in all points except the exhaust port.

The ratio between highest and lowest concentration in the room within one experimental setting had a minimum, 1·5, at half speed ventilation during mock operations, and had a maximum, 2·4, at full speed ventilation in the empty room.

Fig. 2. Dispersion process when smoke was released close to the operating table.

Peripheral dispersal

When gas was dispersed in the periphery, the concentration was lowest at sampling point B with and without activity and at full and half speed ventilation, but at point A at zero mechanical ventilation.

The highest concentrations were found at point A without activity at full speed ventilation and with and without activity at half speed ventilation, but at point D during mock operation at full speed ventilation.

With no mechanical ventilation the concentrations were above the measuring limit of the equipment at all points except A.

The ratio between highest and lowest concentration in the room at the same ventilation rate had a minimum, 2·6, at half speed ventilation during mock operation, and a maximum, 6·1 at full speed ventilation in the empty room.

The distribution of tracer particles in the room

The mean particle concentrations of four experiments in each setting at different positions and different ventilation rates are given in Fig. 4. The standard deviation of the values between the four experiments never exceeded 10 % of the mean.

Central dispersal

When particles were dispersed at the operating table, the concentration was lowest at sampling point C in all experimental settings. The highest concentrations were found at point A in all settings. The ratio between highest and lowest

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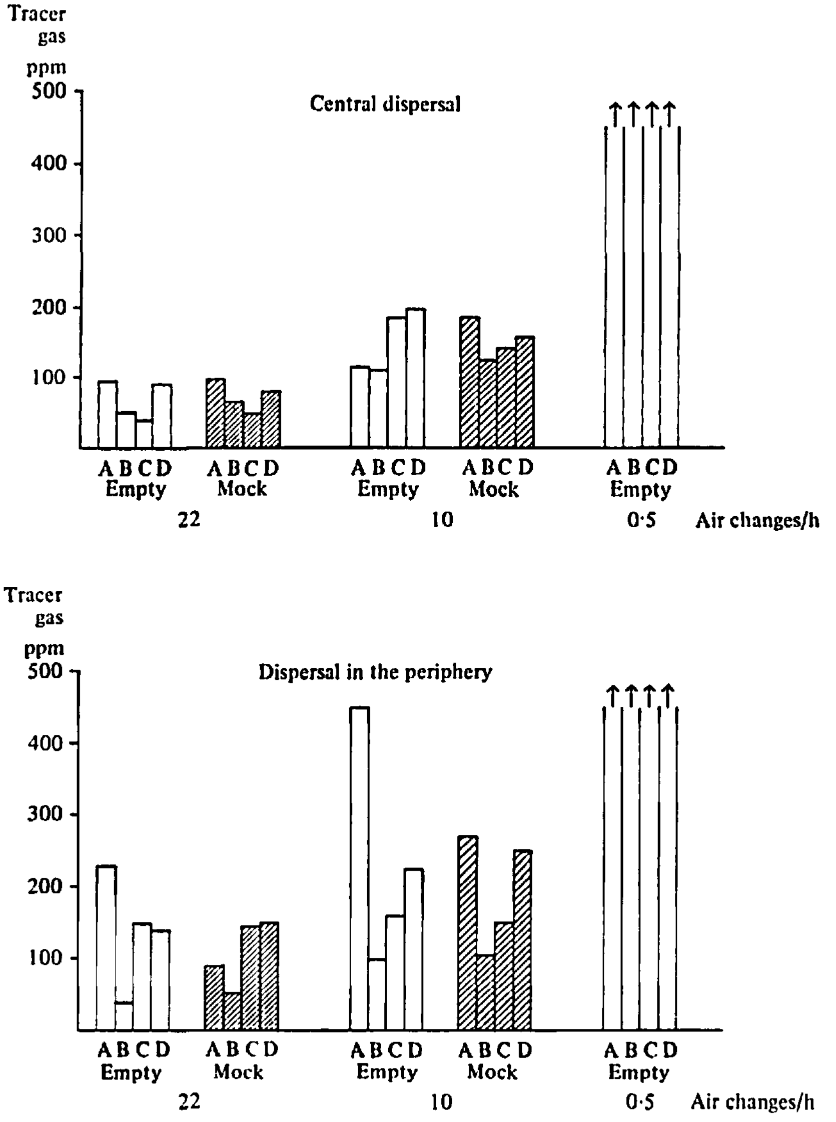

Fig. 3. Distribution of gas (p.p.m.) in the room, in empty room and at mock operation at sampling sites A–D (Fig. 1).

concentration in the room at constant ventilation rate had a minimum, 2·9, at full speed ventilation in the empty room, and a maximum, 5·4, at half speed ventilation in the empty room.

The ratio between particle concentrations at the same sampling point at half and full speed ventilation varied in the empty room from 1·8 (B and C) to 3·4 (A), and during mock operations from 1·6 (D) to 2·1 (C).

Peripheral dispersal

When particles were dispersed in the periphery, the concentrations were lowest at sampling point B both in the empty and occupied room at full speed ventilation and at point C at half speed ventilation and at zero mechanical ventilation.

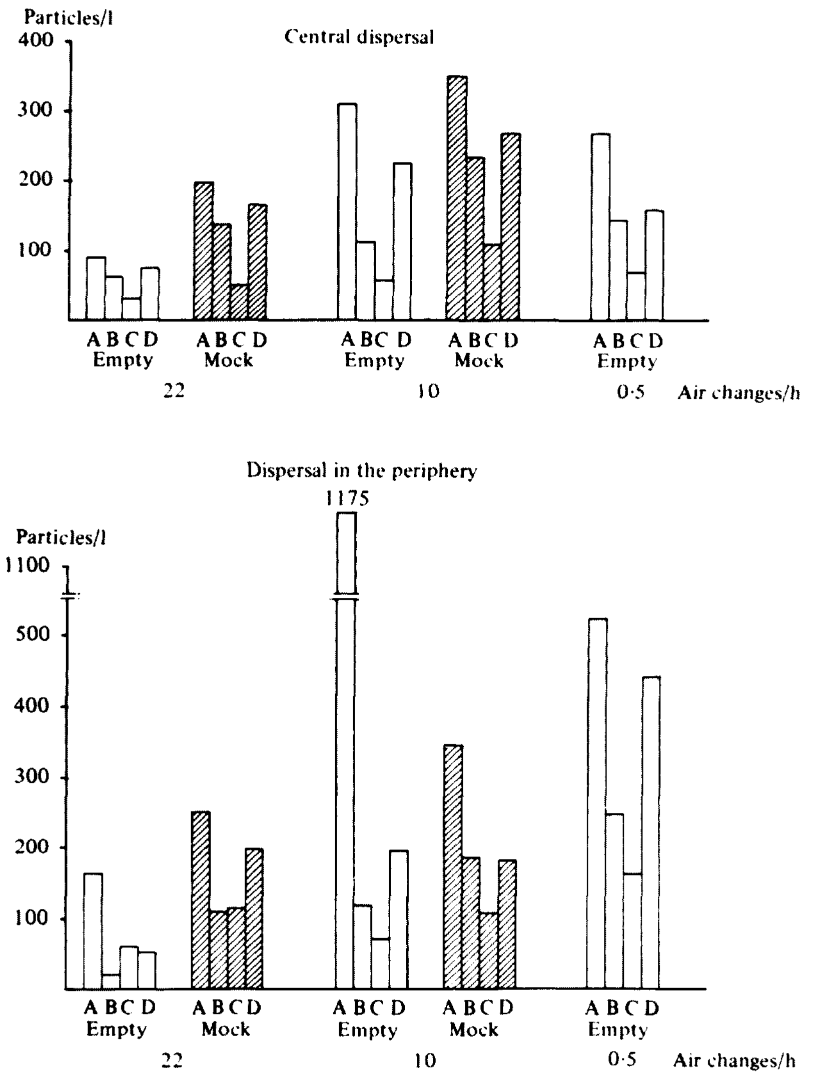

Fig. 4. Distribution of particles (particles/l) in the room, in empty room and at mock operation at the sampling sites A–D (Fig. 1).

The highest concentrations were found at point A in all settings. The ratio between highest and lowest concentrations in the room within the same experimental setting had a minimum, 2·3, at full speed ventilation during mock operations, and a maximum, 16·1, at half speed ventilation in the empty room.

The ratio between particle concentrations at the same sampling point at half and full speed ventilation varied in the empty room from 1·2 (C) to 7·2 (A), and during mock operations from 0·9 (C and D) to 1·7 (B).

Comparison of the distribution of gas and tracer particles

Comparison of gas and particle concentrations using linear regression analysis gave the following results.

Table 1. *Mean levels of gas (p.p.m.) and particles (particles/l) for the whole room*

	Central dispersal				Peripheral dispersal			
	Empty room		Mock operation		Empty room		Mock operation	
Air changes/h	Gas	Particles	Gas	Particles	Gas	Particles	Gas	Particles
22	69	64	74	137	138	74	110	167
10	136	175	151	238	234	390	194	205
0	> 1000	158	—	—	> 1000	343	—	—

Table 2. *Distribution of bacteria in a mock operation setting*

	Number of c.f.u./m³			
	Full ventilation		No ventilation	
Dispersal site	No lamp	Lamp	No lamp	Lamp
At the operating table	125	158	433	367
Under the operating table	150	183	467	433
In the periphery	133	192	450	350

Table 3. *Effect of ventilation on concentration*

Ventilation comparison	Tracer	Dispersal point	Empty room	Mock operations	Calculated
Half speed/ full speed	Gas	Central	2·0	2·0	2·2
	Gas	Peripheral	1·8	1·8	2·2
	Particle	Central	2·5	1·8	1·9
	Particle	Peripheral	4·4	1·2	1·9
No ventilation/ half speed	Gas	Central	> 7	—	20
	Gas	Peripheral	> 4	—	20
	Particle	Central	1·0	—	3·2
	Particle	Peripheral	1·8	—	3·2

With no mechanical ventilation the gas concentrations were maximally high in six of eight settings whereas the particle concentrations were well in the measuring range of the equipment, and statistical comparisons could not be made.

At half speed ventilation, in the empty room at central dispersal the correlation coefficient was 0·26 and at peripheral dispersal 0·96. In mock operation and central dispersal the correlation coefficient was 0·69, and at peripheral dispersal 0·65.

At full speed ventilation in the empty room at central and peripheral dispersal the correlation coefficients were 0·90 and in mock operations at central dispersal it was 0·97 and at peripheral dispersal 0·11.

Bacteria-carrying particles

The concentration of bacteria (c.f.u./m³) in the air during mock nursing experiments are shown in Table 2. There was no significant difference between the concentrations at the different sampling points with the same experimental setting. The overall ratio between the mean concentration at no ventilation and at full ventilation was 2·7.

DISCUSSION

The distribution of gas and particles in the empty room was studied with three variations in ventilation rates. Mock operations were not performed without mechanical ventilation as this was not thought to be a realistic alternative to present ventilation standards. In one set of experiments gas and particles were liberated from a point close to the operating table to mimic a disperser among the scrubbed staff. In another set of experiments gas and particles were liberated further out in the periphery to illustrate a disperser among the unscrubbed staff. As it has been shown that bacteria-carrying particles are mainly dispersed from the lower part of the body (May & Pomeroy, 1973) the gas diffuser and the spinning disk were placed 0·9 m above the floor.

Distribution in the room

Tracer gas

The values for gas concentrations given in Table 1 are mean values obtained by visual assessment from the graphical recordings. The concentrations in each experiment sometimes fluctuated violently from zero to about twice the mean value. Theoretical mean values calculated by the dilution principle from the known total output of gas during each experiment would be for full speed ventilation 58 p.p.m. and for half speed 130 p.p.m. All the values found near the operating table were higher than these theoretical values by a factor of 1·2–2·3 depending on ventilation rate, location of gas diffuser and activity. Values close to the wall (B) and values close to the exhaust grill were sometimes lower than the calculated mean.

Smoke

The smoke technique as a rapid simple method was used to visualize the air distribution pattern in the room before siting the gas and particle sampling points.

Velocity measurements

The velocity fluctuations measured in the room were violent. Since the hot-wire instrument contains unacceptable errors under these conditions (Hinze, 1975), the real fluctuations were probably even greater. Therefore, no final conclusions about the velocity fluctuations in the room can be drawn, but the greater fluctuations at 22 air changes/h than at 10 air changes/h indicate that the flow pattern was more turbulent at the higher ventilation rate. This increased turbulence might mean (Ljungqvist, 1979) that the distribution pattern of gas and particles should be more similar at 22 air changes/h than at lower ventilation rates.

Tracer particles

The differences between particle concentrations at different sampling points within the same experimental settings were larger than that for gas. It was greatest in the empty room at half speed ventilation, and greatest at peripheral dispersal. Full speed ventilation probably created a better mixing of the air. In mock operations movements caused by people and heat from the lamp seemed to have the same effect. Except for peripheral dispersal at full speed ventilation the lowest value was always at the exhaust port (point C). The highest values were always found in one of the corners (point A) although this was closest to the source only at peripheral dispersal. The sampling point to the operation table was closest to the source at central dispersal but the concentration there was slightly less than maximum.

The effect of ventilation on gas and particle concentrations

The estimation of particle-output from the spinning disk was not sufficiently accurate to allow for a calculation of the theoretical mean concentration at the various ventilation rates.

The expected ratios between concentrations of air contaminants at different ventilation rates can, however, be calculated using the formula $Ne = B/(R+S)$, where Ne is the equilibrium level, B the rate of dispersal, R the ventilation rate and S the rate of loss due to sedimentation (Bourdillon *et al.* 1948).

With no mechanical ventilation R was 0·5. S is 0 for gas and 3·8 for particles with a sedimentation rate of 0·2 m/min in a room of 3·2 m height. Assuming a constant rate of dispersal $Ne_{1/2}/Ne_{1/1}$ would be $(22+S)/(10+S)$ or 2·2 for gas and 1·9 for particles. $Ne_0/Ne_{1/2}$ would be 20 for gas and 3·2 for particles. The measured ratios are presented in Table 3.

For gas the theoretical values were close to the measured values in each site except at the exhaust port (C), where it was higher at central dispersal and close to 1 at peripheral dispersal. The size of the variations in gas concentration in different parts of the room was of about the same order as that due to ventilation. The results indicate an uneven but fairly stable pattern of air movement in the room. For particles, an increased ventilation from 10 to 22 air changes gave a higher measured mean ratio than that theoretically calculated in the empty room but a slightly lower one during mock operations. In both full speed and half speed ventilation the level of particle concentration was higher than in the empty room.

The effect of increasing the ventilation from 0·5 to 10 air changes/h could not be exactly calculated for gas but was estimated to be within the expected range. For particles the effect was less than expected especially at central dispersal.

The incomplete mixing of the incoming clean air with the contaminated air influences the distribution of particles more than that of gas when the ventilation rates are low and when there is activity in the room. Correspondingly, the correlation coefficients between gas and particle measurements are high at full speed ventilation only.

At peripheral dispersal a low correlation between gas and particle measurements in full ventilation during mock operation and a high correlation in half speed ventilation in the empty room was found. This could be explained by the position of sampling point A, which was close both to dispersal source and exhaust port. Smoke studies indicated a great instability in concentrations in this point depending on movements in the room.

A comparison of the effect of ventilation on bacteria-carrying particles with that on tracer particles showed that $Ne_0/Ne_{1/1}$ for bacteria-carrying particles at the three sampling points varied between 3·5 and 1·8 and was thus close to the values found for particles, central dispersal, which varied between 3 and 2·1. These ratios are about half of that theoretically calculated, which is $1·9 \times 3·2 = 6·1$.

Our findings are not in agreement with the findings of Wiegersma (1980) who showed a good correlation between the distribution of gas and bacteria. The reason for this is probably that he used aerosolized bacteria and these are much smaller than bacteria-carrying particles and the potassium iodide particles used in this investigation.

CONCLUSIONS

Judging from gas and particle measurements the ventilation system of this operating theatre supplies air that is unevenly distributed, and not used effectively in the region supposed to be clean, i.e. the surgical area.

Conclusions from simple gas measurements as to the probable distribution of bacteria-carrying particles, can only be drawn at fully developed turbulent air movements. This degree of turbulence was fulfilled in this operating theatre at 22 air changes/h.

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