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Bacteriological evaluation of a laminar cross-flow tunnel for surgery under operational conditions

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SUMMARY

A transportable surgery cross-flow unit has been tested under 'operational conditions'. By the use of artificial aerosols and a volunteer surgical team, or dummies, it was found that, at an air velocity of 0·45 m./sec., a detectable transfer to above the table occurred only when quite highly concentrated aerosols (of more than $10^{3·6}$ bacteria/m.^{3} of air or more) existed underneath the table. The short disappearance time under these conditions and the quite stable flow pattern above the table found when a surgical team was working, standing along both sides of the table, make it unlikely that an aerosol of detectable concentration can develop during surgery, at this site. The chance that particles, liberated from the heads of the surgical team, settle on the table, was found to be strongly reduced when a cross-flow tunnel operated at an air velocity of 0·45 m./sec. The transfer from outside the unit to the inside was prevented by closing the upper part of the open front side.

INTRODUCTION

In recent years an increasing number of studies on the use of unidirectional flow (U.D.F.) in operating theatres has been reported in the literature. They often deal with the advantage(s) of cross-flow over down-flow or vice versa (Scott, Sanderson & Guthrie, 1971; Whyte & Shaw, 1971). Cross-flow seems to offer two practical advantages over down-flow: (1) little or no disturbance of the flow pattern by a standard operation lamp; (2) cross-flow units are easier to install in conventional operating theatres. They do not necessarily require major changes in the building. At relatively little cost, conventionally ventilated operating rooms can, if necessary, be changed into laminar flow ventilated ones. For this purpose, mobile U.D.F. cross-flow tunnels are on the market. It is claimed that these units considerably reduce the risk of airborne contamination when they are operated at an air velocity of 0·45 m./sec. Since the ventilation of a number of existing operating theatres requires improvement, particularly those for 'ortho-paedic', 'neuro'- and 'open heart' surgery, we considered it necessary to test such a cross-flow unit.

To obtain a good insight into the functioning of the unit under operational conditions, several parameters were studied:

(*a*) The transfer of bacterial aerosols from outside (upstream) the unit to the

inside. This should not occur, even during activities such as that of the 'circulating nurse'.

(*b*) The occurrence of transfer of bacterial aerosols from underneath as well as from behind the members of the surgical team to above the operation table.

(*c*) The disappearance time of bacterial aerosols, i.e. the time elapsing between aerosolization of bacteria and the moment that the 'last cell' of that aerosol is sampled, was determined above and underneath the table.

(*d*) The correlation between bacterial concentration/m.^{3} of air and the occurrence of fall-out above and underneath the table was investigated.

(*e*) The deviation from horizontal transport of aerosol particles in the cross-flow area. This was studied to obtain information on the fate of bacteria generated from the heads of the surgical team.

All tests were performed with bacterial aerosols of different concentrations and at three different air velocities: 0·45 m./sec.; 0·25 m./sec. and with the air flow off. In this way, a fuller insight could be obtained into the conditions under which transfers occurred.

MATERIALS AND METHODS

Cross-flow unit

For our study an Enciramedic 'surgery isolator for sepsis control' was used, made under Envirco's licence by CEAG Schrip Reinraumtechnik in Germany. The size of the filter wall was 3·20 m. × 2·80 m. while the tunnel was 3·60 m. deep. This unit could be operated with an air velocity at the site of the filter wall of 0·25 and 0·45 m./sec. The flow pattern was not turbulence-free at an air velocity of 0·25 m./sec. This improved considerably when the unit was operated at 0·45 m./sec. A dummy operating table with standard dimensions was placed inside the unit near the filter wall (figure 1). During the first four experiments, the influence of 'surgical activity' by a team of four volunteers imitating surgical activity around the table was studied. For this purpose, the results were compared with those obtained with a dummy team. The dummy team consisted of four puppets of human size. Since no significant differences were found when a human team of four persons was standing around the table or with the immobile dummy team, the remaining experiments were performed with the dummy team. Because some influence on the transfers was noticed when an individual walked inside the enclosure during the experiments, this activity was continued in the experiments with the dummy team around the table. To prevent the occurrence of transfer of bacterial aerosols from outside the enclosure, a P.V.C. flap closing the upper part of the open front side was found necessary (Fig. 1).

Bacterial aerosols

Escherichia coli was used in this study to obtain an adequate decay rate of the aerosolized bacteria (Brown, 1954). In each experiment, three overnight broth cultures of *E. coli* were suspended in water. The suspensions consisted of 10^5, 10^7, and 10^9 bacteria per ml. A spray which aerosolized approximately 1 ml. of

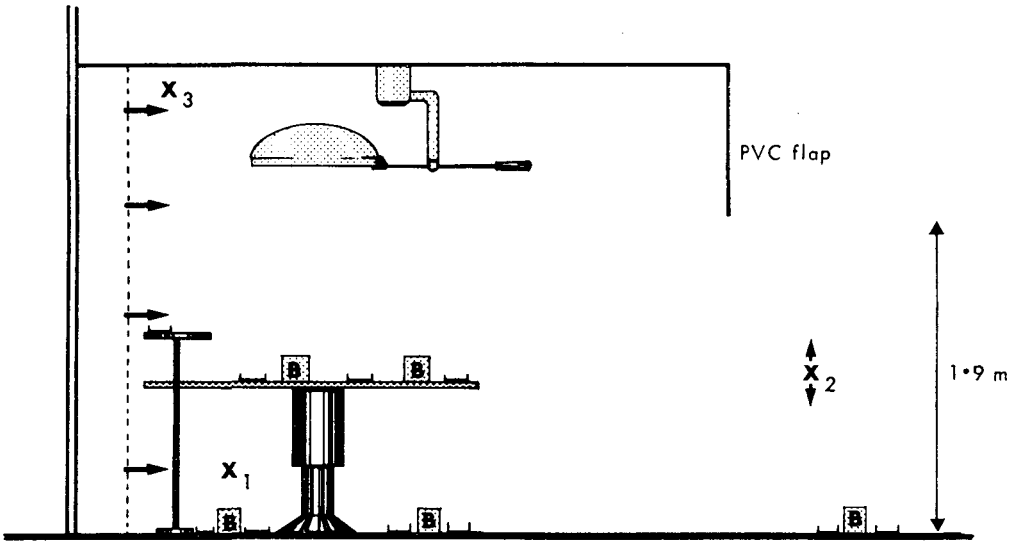

Fig. 1. Schematic drawing of the test situation. The surgical team is omitted from the drawing for the sake of simplicity.

suspension per second was used. In the resulting aerosols, *E. coli* had a decay rate of 0·5–1 % per minute. The experiments were repeated 6 times.

The *E. coli* particles were smaller in size (90 % of the single particles ranged between 0·6 and 3·0 μm. in diameter) than the particles contaminated with bacteria that are generated by human individuals (Noble, Lidwell & Kingston, 1963; Whyte, 1968). The apparent settling velocity underneath the table was estimated according to Foord & Lidwell (1972) and was found to vary between 15 and 29 cm./min.

Aerosolization was performed at several sites (Fig. 1):

(1) Underneath the table to determine the transfer to the air above the table and the fraction that sedimented. Spraying was performed for 20 sec.

(2) Behind the surgeons along both long sides of the table in the direction of the flow. Spraying was performed for 10 sec. at each side.

(3) Outside the unit before the open front side to determine the transfer of cells to the inside of the enclosure. Aerosolization was continued for 15 sec. in each experiment.

(4) Directly in front of the filter plenum near the upper edge. This was necessary in order to study the vertical deviation of aerosolized *E. coli* particles.

All experiments were performed six times so that significant results could be obtained.

Sampling

The four locations of the Bourdillon type 'slit samplers' and the sedimentation plates in the various experiments are shown in Fig. 1. The slit samplers were used to determine the concentration of bacteria in the air after aerosolization as well as the disappearance time. The latter was calculated from the size of the segment of the agar plates which showed *E. coli* colonies after incubation. The rotation speed of the plate during sampling was 3° per sec. The slit samplers were operated at an air sampling volume of 30 l./min. In all experiments, the sampling time was 2 min. After each experiment, the room was ventilated for at least 2 min. by switching on the cross-flow at a 'high velocity' (0·45 m./sec.).

Sampling was performed on Endo agar (DIFCO). By use of this culture medium, the counting of colonies in experiments in which the flow was off, was not hampered by colonies of staphylococci or other airborne bacterial species.

Temperature and humidity. These were not controlled and varied slightly. The temperature varied between 20 and 22° C.; the relative humidity, between 51 and 55 %.

Air velocity. The air velocity was determined with a Wilh. Lambrecht K 6 (Gottingen) hot wire flow meter (type 641 N). During surgical activity inside the enclosure, the air velocity was determined in front of the filter wall as well as at a distance of 2·5 m. at nine different points located 1 m. from each other.

RESULTS

The flow pattern above the table appeared to be quite stable when the cross-flow tunnel, operated at 0·45 m./sec., was in use. In a cross-section through the room at a distance of 2·5 m. from the filter wall (just behind the operating table) the air velocities were measured at nine different points. Greater variations were found when the unit was operated at 50 % of the normal speed than when at full speed (0·45 m./sec.) operation (Table 1). At the site of the filter wall, the air velocity distribution was more homogeneous and varied within the tolerances specified by U.S. Federal Standard, 209 A. Transfer from outside the enclosure was detected only with an aerosol of over 10,000 bact./m.^{3} of air. It could virtually be eliminated with a plastic flap in the open front side extending to 1·9 m. above the floor. This reduced the opening and, therefore, increased the air velocity in the opening to $0{\cdot}66 \pm 0{\cdot}05$ m./sec.

In order to be able to realize the goals outlined in the introduction, it was found necessary to challenge the system with relatively highly concentrated bacterial aerosols. This was particularly necessary to determine the occurrence of a 'transfer' from underneath to above the table and to investigate whether, under surgical (activity) conditions, a transfer could occur from the operating theatre environment into the enclosure.

With the flow switched off, only convection currents and air movements induced

Table 1. *Air velocity (m./sec.) at nine points 1 m. apart, all at 2·5 m. from the filter wall*

Point no.	Half blower capacity		Full blower capacity	
	Flap open	Flap shut	Flap open	Flap shut
1	0·26–0·28	0·26–0·28	0·42–0·44	0·40–0·42
2	0·24–0·26	0·20–0·22	0·38–0·40	0·30–0·32
3	0·26–0·28	0·24–0·26	0·48–0·50	0·40–0·42
4	0·18–0·30	0·24–0·26	0·20–0·30	0·38–0·42
5	0·28–0·30	0·22–0·24	0·46–0·50	0·48–0·50
6	0·22–0·26	0·24–0·26	0·40–0·42	0·46–0·48
7	0·05–0·15	0·16–0·20	0·10–0·30	0·20–0·30
8	0·26–0·30	0·28–0·30	0·53–0·55	0·52–0·54
9	0·18–0·32	0·24–0·26	0·38–0·50	0·52–0·54

The nine points were distributed in a vertical plane as follows:

1 2 3
4 5 6
7 8 9

Table 2. *Transfer and settling of Escherchia coli aerosols inside a cross-flow tunnel operated at different air velocities*

Air velocity (m./sec.)	Mean log bact. (count/m.^{3}) (S.D.)		Transfer index	Average bact. fall-out/m.^{2} above the table in 2 min.	Settling† velocity (cm./min.)
	Underneath the table	Above the table*			
0	2·8 (0·1)	1·9 (0·1)	0·125	1·5	0·93
	3·8 (0·3)	2·6 (0·2)	0·062	5·0	0·62
	4·2 (0·2)	3·1 (0·3)	0·083	16·0	0·61
0·25	2·5 (0·2)	—	—	0	—
	3·7 (0·2)	1·2 (0·1)	0·003	0·8	2·5
	4·4 (0·2)	2·2 (0·2)	0·006	76	2·4
0·45	2·7 (0·2)	—	—	0	—
	3·6 (0·3)	—	—	0	—
	4·3 (0·3)	1·5 (0·2)	0·0015	4·0	6·2
	5·0 (—)	2·5 (—)	0·0031	3·3	5·5

* Mean concentration of two slit samplers (see Fig. 1).
† According to the formula of Foord & Lidwell (1972).

by 'surgical activity' were found. These occasionally resulted in upward-directed turbulences, as were seen during smoke tests. The area directly above the table may have been reached, however, in two different ways: (1) as a result of convection streams and movements from the surgical team; and (2) by air coming from more remote places inside the enclosure. Any person walking inside the enclosure during the test may have contributed to the latter. Under cross-flow ventilation conditions, a different mechanism was presumably responsible for the transfer from underneath the table. Aerosol spread to all sides within the enclosure, as was seen when the flow was off, did not occur, and convection streams induced by the surgical team were no longer found. Upward-directed air movements also

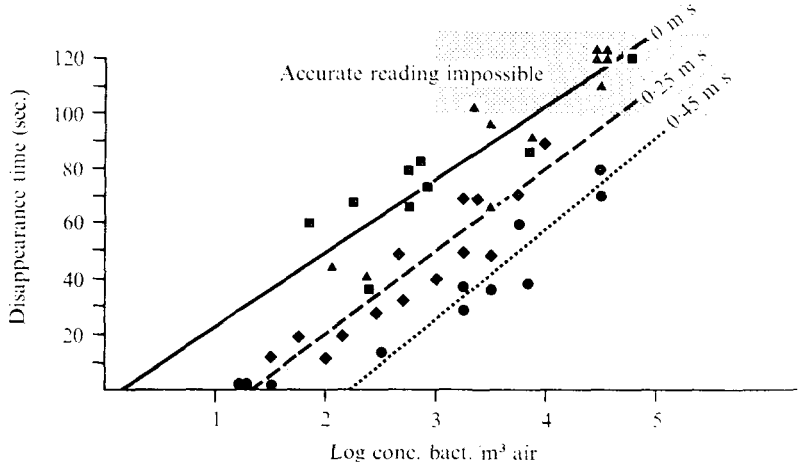

Fig. 2. Disappearance time of several aerosols at air velocities above and underneath the table.

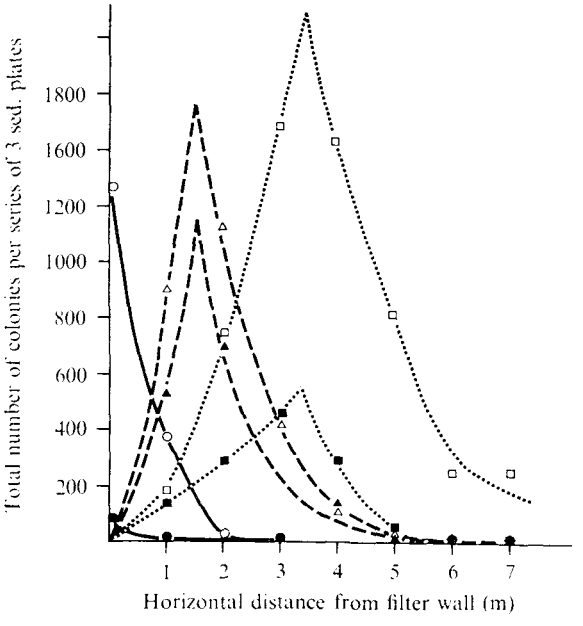

Fig. 3. Sampling on table level at 1 m. intervals (horizontal distance) from the filter wall following aerosolization 1·7 m. above the table directly in front of the filter wall.

occurred under these circumstances, but now owing to disturbances in the laminar flow pattern. These occasional upward-directed air turbulences were made visible by smoke tests and were seen at various places around the table 'down stream' from the members of the surgical team.

The results of the bacterial aerosolization are presented in Table 2. The bacterial counts per m.³ of air which were found in a total of 18 different experiments performed with each air velocity are presented in three classes as the mean log value

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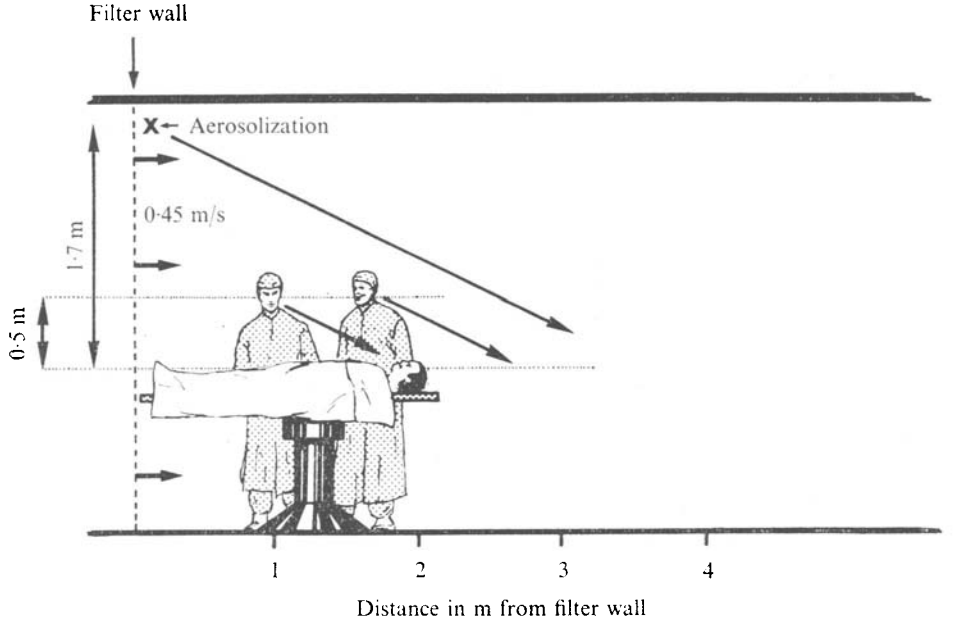

Fig. 4. Diagram showing the vertical displacement of aerosolized bacteria in a cross-flow of 0·45 m./sec.

(and S.D.) of five to seven observations. When the unit was operated at 0·45 m./sec., a few extra experiments were performed. In one of these a very dense aerosol of 10^5 cells/m.^{3} of air was achieved underneath the table (Table 2). The Transfer Index (Lidwell, 1960) calculated from these data shows some fluctuation at each air velocity, but decreased significantly in value at increasing air velocity. A less favourable observation was that the sedimentation of the *E. coli* particles increased considerably when the flow was increased (Table 2). The transfer index of experimental aerosols generated behind the members of the team when standing along both long sides of the table to above the table was zero, even when suspensions of 10^7 bacteria/ml. were aerosolized.

The disappearance time of aerosols above and underneath the table should be as short as possible. This has become an important requirement, since we have indicated that settling above the table is adversely influenced by higher (cross-flow) air velocities (Table 2). The disappearance time was found to be greatly reduced at increasing air velocities (Fig. 2). For an aerosol of about 500 bacteria per m.^{3} of air, the average disappearance time was found to be 16 sec. at an air velocity of 0·45 m./sec., 42 sec. at 0·25 m./sec., and 72 sec. when the flow was switched off.

The site of settling of bacteria shed from the heads of the operating team was approximated by aerosolization of bacteria at 1·70 m. above the table. The experimental aerosol was made as high as possible above the table in order to assure that the 'peak settling' at various air velocities occurred at well separated sites. No bacteria sedimented on the table from the heads of the team under operation conditions. This was also found in a previous study (Van der Waaij,

unpublished data). Inconclusive results were obtained by aerosolization of bacteria at 50 cm. above the table (approximate distance of the heads of the surgical team above the table). However, by following aerosolization of highly concentrated suspensions from high above the table (1·70 m.), an area could be found 'down stream' where peak settling on the table occurred (Fig. 3). The estimated area of 'peak settling' of bacteria generated at 50 cm. above the table is shown in Fig. 4.

DISCUSSION

The results of the present study indicate that, during surgery, inside a cross-flow tunnel operated at an air velocity of 0·45 m./sec., quite highly concentrated bacterial aerosols are required underneath the table to accomplish a transfer of bacterial aerosol particles to above the table. At an air velocity of 0·45 m./sec., an aerosol of $10^{3·6}$ bacteria per m.^{3} underneath the table did not result in a measurable transfer (Table 2). It should be realized, however, that the time that the aerosol existed underneath the table was short. An aerosol of 10^3 bacteria/m.^{3} of air remained only a little longer than the time during which it was generated, namely, 30 sec. (Fig. 2). The members of a surgical team will shed most bacteria from the lower half of their body (May & Pomeroy, 1973) and consequently underneath the table. After having worn a surgical gown for 4 hr., an individual may disperse quite a number of *Staphylococcus aureus* cells which can result in a concentrated aerosol (of up to 1000 cells/m.^{3} of air in an unventilated enclosure of 30 m.^{3}) according to Blowers, Hill & Howell (1973). When it is taken into consideration that the particles used in our study were smaller and had a lower settling velocity than the bacterially contaminated particles shed by humans, we can assume that our test situation was less favourable for the prevention of a transfer than is the case when these larger particles must be transferred. Secondly, the rapid disappearance time, which is also favourably influenced (shortened) by a higher settling velocity, will prevent the formation of concentrated aerosols such as Blowers described. This means that, even in the extreme case in which the surgical team consists exclusively of *S. aureus* dispersers and an aerosol of 10^3 cells/m.^{3} could persist for a short time underneath the table, the chance of a transfer to above the table is small. Bacteria dispersed inside the enclosure behind the team (for example, by a circulating nurse) will only be transferred to above the table when the source moves upstream from the table and at the level above the surface of the table. Bacteria liberated by the surgeons above the table are apparently the only ones that may contaminate the drapes or the wound. We have found that the settling velocity was increased about sixfold when the air velocity was increased from zero (unit switched off) to 0·45 m./sec. Particles dispersed 50 cm above the table will, according to our findings, land on the drapes about 1 m. down stream. This means that particles shed from the heads of the team members will generally not settle on the surgical linen but further down stream (Fig. 4). This indicates that good shielding of the nose, mouth, and hair is indicated not only in a down-flow set-up, but also under cross-flow conditions. An important difference between the two remains, however, that, in down-flow,

particles liberated from the upper half of the body have, owing to the strongly increased settling velocity (van der Waaij & van der Wal, 1973), an increased chance of landing on the table. Under cross-flow conditions, this may only occur when the particles are liberated at a level of less than 50 cm. above the table by individuals standing along the long side of the table and particularly those at the foot end. The more down stream the surgeons are standing near the 'head end' of the table, the safer is the situation (Fig. 4).

Transfer from outside the enclosure could easily be prevented by reducing the opening in the front side of the cross-flow tunnel so that the air velocity through the opening was increased. It can be concluded, therefore, that cross-flow ventilation of surgical rooms can provide excellent protection from airborne contamination of the wound, instruments, and drapes covering the patient, provided the following points are taken into consideration:

(1) No source of contamination may exist upstream from the table.

(2) Adequate surgical clothing, particularly the use of a good face mask and cap, is necessary.

(3) Bending over the patient to a level less than 50 cm. is potentially dangerous.

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REFERENCES

Blowers, R., Hill, J. & Howell, A. (1973). Shedding of *Staphylococcus aureus* by human carriers. In *Airborne Transmission and Airborne Infection* (ed. J. F. Ph. Hers & K. C. Winkler), p. 432. Utrecht: Oosthoek Publishing Co.

Brown, A. D. (1954). The survival of airborne micro-organisms. Effects of temperature. *Australian Journal of Biological Sciences* **7**, 444.

Foord, N. & Lidwell, O. M. (1972). The control by ventilation of airborne bacterial transfer between hospital patients and its assessment by means of a particle tracer. *Journal of Hygiene* **70**, 279.

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

May, K. R. & Pomeroy, N. P. (1973). Bacterial dispersion from the body surface. In *Airborne Transmission and Airborne Infection* (ed. J. F. Ph. Hers & K. C. Winkler), p. 426. Utrecht: Oosthoek Publishing Co.

Noble, W. C., Lidwell, O. M. & Kingston, D. (1963). The size distribution of airborne particles carrying microorganisms. *Journal of Hygiene* **61**, 385.

Scott, C. C., Sanderson, J. T. & Guthrie, T. D. (1971). Choice of ventilation system for operating theatres. *Lancet* i, 1288.

Waaij, D. van der & Wal, J. F. van der (1973). 'Laminar' airflow ventilation: crossflow or downflow? In *Airborne Transmission and Airborne Infection* (ed. J. F. Ph. Hers & K. C. Winkler), p. 584. Utrecht: Oosthoek Publishing Co.

Whyte, W. (1968). Bacteriological aspects of air-conditioning plants. *Journal of Hygiene* **66**, 567.

Whyte, W. & Shaw, B. H. (1971). An experimental down/cross flow operating room. *Contamination Control* **10**, 6.