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# Bacteriological evaluation of a mobile laminar cross-flow unit for surgery, under laboratory circumstances

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SUMMARY

A mobile laminar cross-flow unit for surgery has been evaluated by the use of an experimental bacterial aerosol of *Escherichia coli* in different concentrations, generated at several different sites. A separate ventilation system, mounted underneath the table, produced an almost downward directed curtain of sterile air along both sides of the table. When the velocity of the air stream, discharged by the cross-flow unit, was adjusted at 0·50 m./sec. at 2 m. from the filter face (at the head end of the operation table), the surface of the table could be maintained free of bacterial settling, even after aerosolization of heavily concentrated suspensions of $10^8$ bacteria/ml. at different sites outside the enclosure and underneath the table as well.

## INTRODUCTION

In a previous publication (van der Waaij, Heidt & Hendriks, 1974) bacteriological test results of a cross-flow tunnel for surgery were described. It was found that, under cross-flow conditions of sufficient air velocity (0·50 m./sec.), transfers of bacterial aerosols to the area above the operation table (Lewis *et al.* 1969) were considerably reduced. However, due to upward directed air turbulences down stream from the members of the surgical team standing around the table, contaminated air from underneath the table apparently now and then reached the table surface. Because of the strong 'diluting' effect of the (cross-flow) ventilation (which existed also underneath the table) on bacterial aerosols generated at that site, the fraction of the original aerosol reaching the air above the table was very small.

In an attempt to reduce the costs of such a cross-flow ventilation system, the filter surface was reduced to a workable minimum. Apart from cost price reduction, this had another practical advantage: as a result of the reduced blower capacity required, the increase in room temperature due to heat produced by the blowers could be controlled by a standard ventilation system present in almost every operating room.

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To further limit the occurrence of a transfer from underneath the table a special ventilation system was mounted there. This unit produced a downward-directed 'curtain' of sterile air. If this 'air curtain' was of a sufficient velocity it appeared to prevent almost completely the transfer of bacteria from underneath the table to the area above the table as well as to the shelves directly in front of the filter face which were meant as an instrument table. The bacteriological results obtained with this unit during actual surgery will be published in two subsequent publications. The first will deal with the results obtained with the cross-flow unit without the additional ventilation underneath the table. In a subsequent study, which is still being continued, the effect of the additional ventilation underneath the table on bacterial settling on the table will be described.

## MATERIALS AND METHODS

### *Cross-flow unit*

A unit coded OPC 122–244, based on our laboratory model (van der Waaij, Vossen & Korthals Altes, 1973) and built by the firm of Pielkenrood Vinitex in The Netherlands, was used. The dimensions of the unit (Fig. 1) were 2·58 m. wide, 1·55 m. deep, including the enclosure with the shelves for sterile storage of surgical instruments (but excluding the plastic drapes forming the side walls), and 2·00 m. high. The surface of its filter face was $2{\cdot}4 \times 1{\cdot}2$ m. The filters and their setting in the units were leak-tested with a Royco particle counter and appeared leak-free. A dummy operating table of standard dimensions was placed inside the unit; the foot-end of the table was directed towards the filter wall. A dummy operating team, consisting of four puppets of human size, was placed around the table (two along each side), and a dummy patient, covered with standard surgical drapes, was placed on the table. The puppets forming the team were heated to body temperature with electrical bulbs. A small blower with variable-speed controls was mounted underneath the operating table and connected with a prefilter and a HEPA filter, respectively, at the inlet and outlet sides. The filtered air was conducted through pipes of 7 cm. diameter to pipes of the same size mounted 30 cm. underneath the edges of both long sides of the table. These pipes of 130 cm. length had a series of 25 openings of 1·3 cm. diameter in a row at 5 cm. distance from each other (Fig. 1). In this way an air curtain of sterile air could be provided, the direction and velocity of which could be adjusted. For sterile storage of surgical instruments, shelves of sufficient length and surface for the instruments were constructed directly in front of the filter wall (Fig. 1).

### *Bacteriological test*

The bacteriological evaluation was very similar to the one described in a previous publication about the test results of a cross-flow tunnel (van der Waaij *et al.* 1974). Nine ml. of an overnight culture of the same *Escherichia coli* strain in brain–heart infusion broth was used for aerosolization. The suspensions aerosolized contained $10^4$, $10^6$ and $10^8$ bacteria/ml. and were nebulized in amounts of 9 ml. which took 9–10 sec. Furthermore, the nozzle used for spraying in the present study generated bigger droplets which resulted in an aerosol of particles consisting

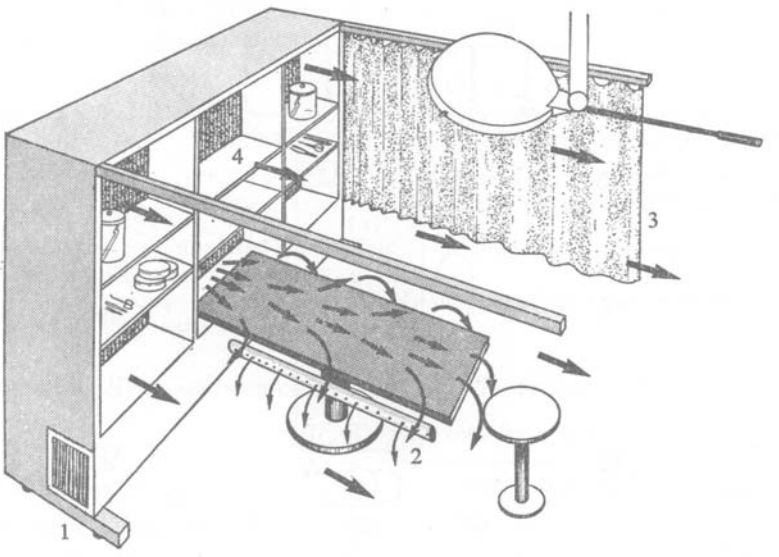


Fig. 1. Diagram of the unit showing the flow pattern over the operation table. 1, Prefilter in the side wall; 2, pipes about 30 cm. underneath the table surface with a row of openings through which an almost downward directed air curtain is produced; 3, plastic drapes forming the side walls of the enclosure; 4, shelves for sterile surgical instruments.

of bacterial clusters. The latter had an average diameter of 3 $\mu$m. The mean sedimentation velocity of these particles was consequently higher than in our previous communication. This made the test results more comparable with the results in operating rooms during surgery when aerosols of human origin existed. The particles of the latter have an average diameter of 10 $\mu$m. (Bernard, Speers, O'Grady & Shooter, 1965; Whyte, 1968) and a mean sedimentation velocity of 30 cm./min. (Foord & Lidwell, 1972).

The suspensions were aerosolized at five different sites (see Fig. 2): (1) underneath the table; (2) in front of the unit (1 m. from the head-end downstream of the table, but above the level of the table); (3) left and right of the unit; (4) above the unit. During the latter experiment the table was elongated from 2 to 5·5 m. Each experiment was performed 4 times.

Air samples were taken with three 'slit samplers' and a series of 36 settle plates in each experiment. Sampling began at the same time as aerosolization of *E. coli*. The location of the slit samplers and the plates is shown in Fig. 2. The surface area of each settle plate was 64 cm.$^2$. The sampling time was 1 min. This short sampling time was necessary because of the rapid decay rate of this aerosol. A slight reduction was found only 1 min. after spraying and the survival was almost zero after 20–30 min. The air samples were taken on Endo agar (DIFCO). On this medium counting of colonies in experiments in which the air flow was turned off was not hampered by colonies of staphylococci or other airborne bacterial species.



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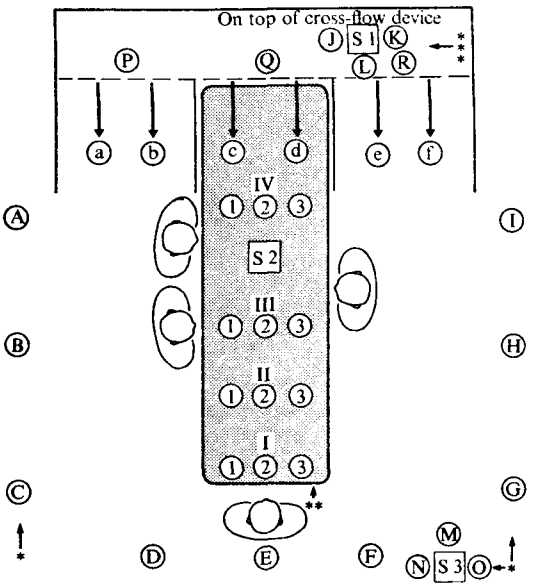


Fig. 2. Floor plan showing the location of the settle plates and slit samplers (S) during the experiments. Slit sampler S 3 and plates N, M and O were located underneath the table in all experiments. Slit sampler S 1 and plates J, K and L were always placed at the site of aerosolization of the *E. coli* suspension. * Site and direction of aerosolization of the suspension, left or right of the unit, 1·3 m. above the floor. ** Site and direction of aerosolization of the suspension, underneath the table, just above floor level. *** Site and direction of aerosolization of the suspension, above the unit, 2·5 m. above the floor.

*Temperature and humidity*

These were not controlled and varied slightly. The temperature varied between 19 and 23° C.; the relative humidity between 45 and 51 %.

*Air velocity*

The air velocity was determined with a Wilh. Lambrecht (Göttingen) hot-wire flow meter (type 641N).

Before the experiments were started, but after the dummy conditions were set up, the air velocity was determined in a vertical cross-section parallel to the filter wall at distances of 0·50 and 2·00 m. from the filter wall. In each cross-section the air velocity was determined at 220 points at a distance of 10 cm. from each other while the blower capacity of both blower units was set at 70 %.

## RESULTS

As shown in Table 1, a sufficient air velocity of more than 0·45 m./sec. could be maintained at the far, head end of the table when the speed of the blowers was set at between 60 and 70 %. This produced an average air velocity of 0·55 m./sec. in the area above the table. During the bacteriological experiments the air velocity at 2 m. from the filter face was set at either 0·5, 0·25 or 0 m./sec.

The optimal direction for the 'air curtain' underneath the table was found to be

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Table 1. *Mean and* S.D. *of air velocities (m./sec.) above the table* in two vertical cross-sections parallel to the filter face at different distances from the filter*

| Distance from filter-wall (m.) | Part of the air column | | |
|---|---|---|---|
| | Left (0·7 m.²)† | Centre (0·8 m.²)† | Right (0·7 m.²)† |
| 0·5 | 0·593 ± 0·141 | 0·560 ± 0·130 | 0·684 ± 0·135 |
| 2·0 | 0·463 ± 0·120 | 0·462 ± 0·86 | 0·523 ± 0·212 |

* Only air velocities measured above the table corresponding with the upper 2·2 m.² of the filter face are reported in this table.

† Surface of the filter face corresponding with the surface of the cross-sections in which the air velocity at 77–88 different points was determined.

Table 2. *Mean sedimentation velocity at the various sample sites*

| Sampling site | Sed. velocity (cm./min.) at | | |
|---|---|---|---|
| | 0 | 0·25 m./sec.* | 0·50 m./sec.* |
| Above the table | 9·0 | 52·4 | 36·0 |
| Underneath the table | 10·2 | 10·4 | 29·9 |
| Outside enclosure | 13·4 | 9·3 | 17·5 |

* Air velocities were measured 2 m. downstream of the filter face at the head-end of the operation table.

at an angle of approximately 35° from the vertical. The optimal air velocity was 2 m./sec., measured at 10 cm. from the openings. This air curtain induced an air stream between the members of the operating team downward over the floor towards the gap (of 50 cm.) underneath the plastic drapes which formed the side walls of the enclosure. In this way the air curtain appeared to shield and eliminate the potentially contaminated air from underneath the table to the sides outside the enclosure. In addition, it induced a slight downward-directed air stream between the 'surgeons' instead of the upward directed turbulences seen when the 'under-table ventilation system' was switched off. If the air curtain was directed too horizontally, part of it bent upward along the side drapes and from there mixed with the air above the table. A completely vertically directed air curtain was also ineffective as it had little effect on the upward-directed air turbulences downstream (in the cross-flow) of the members of the surgical team.

The settling velocity, as determined with the slit samplers in combination with settle plates after Foord & Lidwell (1972), appeared to be lower outside the enclosure than inside (Table 2). With this information, the aerosol transfer as defined by Lidwell (1960) from the various sites of aerosolization to the surface of the operating table can be calculated from the settle plate counts. Because in surgery, however, the main interest concerns settling on the table and not so much the bacterial count in the air above the table, only the settling data are presented. As shown in Table 3, the 'under-table ventilation system' reduced the transfer as expressed in the mean fall-out originating from the four aerosolization points outside the enclosure and from underneath the table as well. The mean fall-out per plate at the sites of aerosolization was $\geqslant$ 1000 when a suspension of $10^8$ bacteria/ml.

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Table 3. *Settling of bacteria-carrying particles within the working area (mean numbers per settle plate)*

| Position of aerosol generation | Sampling row | Air velocity at filter face (m./sec.) 0·5 | 0·5* | 0·25 | 0·25* |
|---|---|---|---|---|---|
| In front of unit | I | 0·50 | 8·98 | 2·09 | 9·72 |
| | II | 0·11 | 2·98 | 0·22 | 4·88 |
| | III | 0·00 | 0·00 | 0·11 | 0·00 |
| Left side of enclosure | I | 0·11 | 0·55 | 0·46 | 2·85 |
| | II | 0·00 | 0·00 | 0·03 | 1·38 |
| | III | 0·00 | 0·00 | 0·00 | 0·00 |
| Right side of enclosure | I | 0·19 | 0·48 | 0·56 | 3·47 |
| | II | 0·00 | 0·00 | 0·00 | 0·70 |
| | III | 0·00 | 0·00 | 0·00 | 0·03 |
| Underneath the table | I | 0·11 | 0·97 | 0·87 | 23·85 |
| | II | 0·11 | 2·63 | 0·18 | 32·33 |
| | III | 0·00 | 1·18 | 0·00 | 2·41 |

No colonies were recovered in any experiment from the plates exposed on the shelf or in row IV.

The figures obtained from four sets of observations at each of the three dilutions of *E. coli* sprayed have been combined to give the mean value for challenge with the $10^8$/ml. suspension. (For this purpose recoveries from the $10^6$/ml. suspension have been multiplied by 2·5 and those from the $10^4$/ml. suspension by 5.)

The position of aerosol generation is given in Fig. 2.

* With the 'under-table ventilation' off.

Table 4. *The sum of the mean settling data found on the plates in row I after aerosolization of different concentrated suspensions at four different sites* with the under-table ventilation system* (U.T.V.) *on and off*

| Concentration of suspension | U.T.V. off 0·25 m./sec. | 0·50 m./sec. | U.T.V. on 0·25 m./sec. | 0·50 m./sec. |
|---|---|---|---|---|
| $10^8$/ml. | 38·85 | 10·49 | 4·01 | 1·91 |
| $10^6$/ml. | 13·83 | 5·24 | 2·17 | 0·33 |
| $10^4$/ml. | 9·25 | 2·25 | 0·50 | 0 |

* In front, left side and right side of the enclosure and underneath the table.

was nebulized, approximately $10^3$ following aerosolization of $10^6$ bacteria/ml. and 130 when a suspension of $10^4$ bacteria/ml. was used. Even at a reduced air velocity of 0·25 m./sec. at the (head) end of the enclosure, a remarkable beneficial effect from the 'under-table ventilation' was seen. The settling on the plates in row I on the table was not proportional to the concentration of the suspension nebulized, either when the 'under-table ventilation' was on or when it was off (Table 4). The relation appeared to be more nearly logarithmic.

To investigate to what extent contaminated air from above the unit, attracted by and mixing with the air curtain underneath the table, could reach the surface of the operating table, aerosols were generated above the unit when it was operated at different air velocities. The results shown in Fig. 3 indicate that settling occurred

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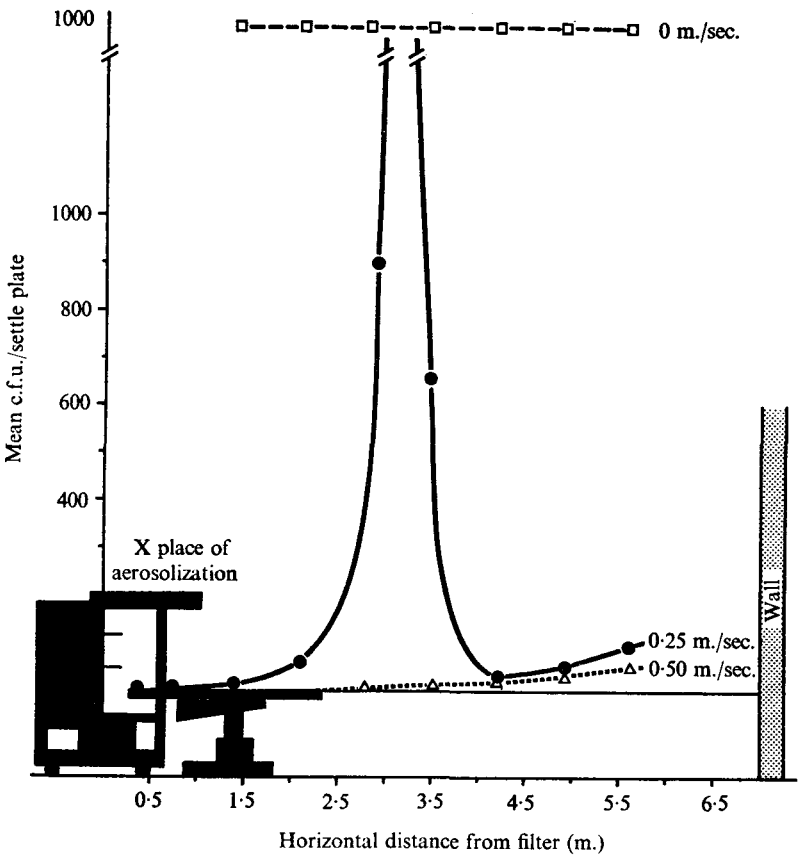


Fig. 3. Shows the settling on the table, or its horizontal extension, following aerosolization above the unit at varying air velocities (0, 0·25 and 0·50 m/sec.).

on the table only at a reduced air speed of 0·25 m./sec. with a peak value at table level some distance beyond the end of the table. Towards the end of the room at about 1·5 m. from the wall, another, but lower, peak of bacterial fall-out was observed.When the air velocity was 0·50 m./sec., this was the only peak that was seen.

The transfers from the various aerosolization sites to sampling sites other than those on the operating table are presented in Table 5. The greatest fall-out was always in the region of nebulization. High values were also recorded at all points when nebulization took place in front of the enclosure, to the sides of the enclosure when nebulization took place above it, and in front of the enclosure with nebulization beneath the table. No substantial transfer to any other site was observed when nebulization took place to either side of the enclosure. It is remarkable that a substantial transfer of aerosol produced from underneath the table appeared to occur to the front. This indicates that a considerable fraction was expelled from directly underneath the table top, because directly above the floor the air stream had an opposite direction, i.e. towards the unit, as indicated by smoke tests.

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Table 5. *Transfer of* E. coli *aerosols after nebulization of* $10^8$ *bacteria/ml. indicated by the mean fall-out in and around the enclosure*

| | | Mean no. of c.f.u./plate in 4 experiments | | | | |
|---|---|---|---|---|---|---|
| Aerosol site | Air velocity (m./sec.) | Under table (plates N, M, O) | In front of enclosure (plates D, E, F) | Left of enclosure (plates A, B, C) | Right of enclosure (plates G, H, I) | Above unit (plates P, Q, R) |
| Under table | 0·25 | ⩾ 1000 | 573 | 3·7 | 18·7 | 40·0 |
| | 0·45 | ⩾ 1000 | 135 | 4·5 | 1·3 | 2·3 |
| In front of enclosure | 0·25 | 190 | ⩾ 1000 | 357 | 227 | 297 |
| | 0·45 | 194 | ⩾ 1000 | 647 | 243 | 690 |
| Left of enclosure | 0·25 | 25·6 | 53·3 | ⩾ 1000 | 12·3 | 27·3 |
| | 0·45 | 24·2 | 56·0 | ⩾ 1000 | 6·3 | 25·0 |
| Right of enclosure | 0·25 | 1·0 | 31·0 | 0·7 | ⩾ 1000 | 11·0 |
| | 0·45 | 2·3 | 9·0 | 0·3 | ⩾ 1000 | 2·3 |
| Above unit | 0·25 | 0·7 | 4·0 | 421 | 382 | ⩾ 1000 |
| | 0·45 | 1·2 | 11·3 | 286 | 203 | ⩾ 10000 |

When the ventilation system was not in use (zero air velocity) the fall-out was > 1000 at all sampling points whatever the site of nebulization.

## DISCUSSION

The results obtained in this study indicate that under laboratory conditions adequate protection from airborne contamination can be obtained from a relatively small-sized laminar cross-flow unit. Inside an enclosure of 2·6 m width and 1·6 m length, which is sufficient space for most types of surgery, an environment can be established with no measurable fall-out on the operating table even following excessive contamination of environmental air. A height of the filter wall of 1 m. above the table appeared sufficient to prevent bacterial fall-out on the table due to mixing of contaminated air from above the unit with the cross-flow, provided the foot-end of the table was placed close to the filter wall and the cross-flow air velocity was 0·50 m./sec.

The measurements of the air velocities indicated that, in spite of the many obstructions formed by the dummy surgical team, patient and instruments, the flow pattern was sufficiently constant in the three parts of the two cross-sections in which it was determined. In the bacteriological experiments the air velocity was adjusted to 0·5 or 0·25 m./sec. The loss of air velocity at between 0·5 m. and 2·0 m. from the filter grid appeared to be moderate, on average about 0·15 m./sec. at the higher air speed.

The numbers of colonies settling were not proportional to the bacterial density of the suspensions nebulized. Presumably the numbers of bacteria-carrying particles generated were only slightly increased by using denser suspensions, but the airborne particles carried a much larger number of bacterial cells.

The sedimentation velocity of the generated particles appeared to be somewhat higher in the ventilated area than on the outside. This is in agreement with

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previous observations (Van der Waaij & Van der Wal, 1973) in which the settling velocity was found to be stronger in cross-flow than in the absence of ventilation and stronger under down-flow circumstances than in cross-flow ventilation. The vertical component, although considerably smaller in cross-flow than in down-flow, may be responsible for this. Although the results concerning the sedimentation velocity are not applicable without reserve to those in the operating theatre, where the average aerosol practical size is bigger (Bernard *et al.* 1965; Whyte, 1968; Hambraeus, 1973), our findings concerning aerosol transfers will largely apply to the clinical situation. To what extent this assumption is true will be investigated in a subsequent series of bacteriological observations with the unit described in use during surgery.

The results – i.e. the transfer from underneath the table, where, under surgical circumstances, a relative strong generation of bacteria may be expected (Lewis *et al.* 1965; May & Pomeroy, 1973) – were remarkably improved when an almost downward-directed air curtain was maintained along the sides of the table. It seemed to be important that the plastic drapes, constituting the side walls of the enclosure, should not hang too near to the floor. A gap of 50 cm. between the drapes and the floor appeared sufficient to permit the air of this air curtain to stream freely to the sides outside the enclosure. When the gap was smaller, e.g. 30 cm. or less, upward-directed air turbulences occurred along the drapes, from where apparently a transfer could occur to the area above the table (an experiment not described in this paper).

It is interesting to note that an aerosol produced 1 m. downstream from the operating table, but above the level of the table, resulted in a transfer to the first row of settle plates on the table when the air curtain underneath the table was on. This could only occur at the head-end of the table, because during the experiments described in this paper the air curtain did not exist there. In experiments (not described in this paper) in which the air curtain was extended around the head-end of the table, this transfer did not occur. Anaesthetists, however, indicated that they would be hindered in their activities by the tube at that location.

A considerable transfer from the area in front of the unit was found to occur not only to underneath the table but also to the sides directly outside the enclosure. After aerosolization of the highly concentrated suspension in front of the unit, only a very slight transfer was found to above the unit. The latter observation and the results of the experiments in which the suspensions were nebulized above the cross-flow unit make a transfer from the front side via the area above the unit to above the table unlikely. This applies obviously only to experiments in which the unit was operated at a mean air velocity of 0·50 m./sec. over the table.

Bacterial aerosols appeared to be of small potential danger with regard to contamination of the operating field when generated left or right of the enclosure. The small amount of transfer to other sample sites, other than on the surface of the table, that was found following the heavy aerosols produced by nebulization of the suspensions of $10^8$ bacteria/ml., could be explained by the fact that the air-inlets of the cross-flow unit were not only located in the front directly above the floor, but also in the side walls of the unit. Most of the bacterial aerosols may have

disappeared quickly in the filters of the unit. This becomes more likely when the much stronger transfer of similar aerosols from the front side of the enclosure to the sides is taken into consideration.

The skilful assistance of Mr P. van Galen in the determination of the air velocities is gratefully acknowledged.

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