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Comparison between three air distribution systems for operating rooms

B. Hillerbrant
Fläkt Indoor Climate
Stockholm, Sweden

B. Ljungqvist
The Royal Institute of Technology
Stockholm, Sweden

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B. Hillerbrant
Fläkt Indoor Climate, Stockholm, Sweden

B. Ljungqvist
The Royal Institute of Technology
Stockholm, Sweden

Background

General

In connection with the planned rebuilding and expansion of operating room facilities at the Umeå General Hospital in Umeå, Sweden, the ability of ventilation systems to remove airborne contaminants released during operations has been discussed and debated. To investigate the properties of various supply-air systems, the authors have participated in full-scale tests, in which supply-air systems based on total mixing, displacement ventilation and vertical, downward, unidirectional air flow ("ultraclean air system") have been studied.

The prime task of the ventilation system in an operating room is to provide an acceptable indoor climate for personnel and patients, to remove odors and released anesthetic gases, and to reduce the concentration of particles in room air to reduce the risk for infection in the operated area of the patient.

Experience has shown that eight to ten air changes per hour - about half of the recommended air flow for operating rooms used for general surgery in Sweden - should be able to provide good comfort for personell and patients. As a consequence, demands for comfort assume a subordinated role from the standpoint of air flow.

When inhalation anesthesia is applied, gas leaks mostly through the mask on the patient. Today, there are different types of supplementary air systems to deal with leaking anesthetic gases, such as local exhaust devices and double masks. The former system is reported on in detail in a doctoral dissertation written by Carlsson (1), while the latter is described by Lindkvist et al (2). Leaking anesthetic gases do not play a decisive role in the selection of ventilation technique; instead, bacteriological problems are the main concern, which is covered in this paper.

There are two main principles for supplying air in an operating room. One is "total mixing ventilation", which is based on the concept of mixing incoming air relatively fast with air present in the room, whereby complete mixing is considered achieved.

In the second principle, the air is introduced in a parallel manner through the room. The air can be conveyed from the ceiling to floor, or between two opposite walls, to create a vertical, unidirectional flow.

In recent years experiments have also been conducted with so-called displacement systems - see for example, Järmyr (3). Displacement ventilation is based on introducing impulse-free air at floor level in the room. The air is a few degrees cooler than the room temperature and is more or less conveyed up to exhaust air devices in the ceiling by means of heat produced in the room. The air flow for this system, like that of total mixing systems, is the conventional flow, 2000 m^3/h.

Total Mixing Ventilation

The system for total mixing ventilation, which is most commonly used in Sweden, consists of symmetrically positioned supply-air devices in the ceiling. Air can be alternatively introduced through an inclined screen.

Ljungqvist et al (4, 5, 6) have used both smoke and tracer gas tests to conduct studies in operating rooms using such supply air systems. The tests showed that air, when released in the area around the operating table, disperses upwards, in high concentrations. The flow is rather unstable and can change direction. People, objects, movements and heat radiation can have a decisive impact on the way contaminants are transported.

These test results were confirmed in part by earlier experiments, which will be briefly summarized below.

In reporting the results from field trials in 22 operating rooms, Blowers and Crew (7) described full-scale laboratory tests with various air distribution systems. Here, it was stated that the concentration of contaminants was gradually reduced by increasing the air change rate up to 20-25 times/hour. The authors' expectations about the efficiency of the ventilation systems were not fulfilled, and this was the most surprising conclusion about these field investigations.

Lidwell (8) notes that air movements in a room are so complex that detailed studies will be time-consuming and therefore require a test method with tracer gas, in which the ventilation efficiency is rated by means of an index - "the exposure to contamination" - or the "transfer index". This index is similar to the term discussed so often in recent years as "the local ventilation index".

Using this test technique, Lidwell and Williams (9) conducted studies in operating rooms, especially with small air movements, concluding that high concentrations can be obtained in the operating area, indicating that the efficiency of the ventilaton systems was low.

In a study, Hambraeus et al (10) also demonstrated the importance of good work discipline among personnel in operating rooms with a high air change rate. Traffic to and from the room, as well as the work clothes of operating room personnel, can play a decisive role as sources that disperse contamination.

Ultraclean Air Systems

Specially ventilated rooms - also called "ultraclean air systems" - are used to control bacteria during very demanding operations, notably during orthopedic surgery, and especially during sensitive hip-replacement operations.

This principle, introduced by Charnley (11, 12) is frequently termed Laminar Air Flow (LAF) ventilation, or unidirectional air flow. Both systems aim to achieve an air velocity of about 0.4 - 0.5 m/s in a parallel flow. An air flow of approximately 10,000 - 16,000 m^3/h is thereby achieved, which is 5 to 8 times higher that air flows in conventional, total mixing systems.

Whyte et al (13), Lindberg (14) and Lidwell (15) report that horizontal air distribution contains higher concentrations than vertical flows. A conceivable, and likely, explanation is that operating room personnel block the main flow air, causing wake vortices behind the personnel, resulting in the accumulation of contaminants. Vortices, and the ability of vortices to accumulate contaminants, have been described by Ljungqvist (16). The study in this paper is therefore limited to investigating only the unidirectional system with vertical air distribution, referred to here as the "filter ceiling system."

Descriptions of Tests

Test Methods

In Sweden, Andersson et al (5) reported in a study that room air is well mixed, and that the dispersion patterns for bacteria-carrying particles and gases will both be satisfactory when a conventional air flow is supplied. As a consequence, tracer gas and visualization methods with smoke (particles) can be used in most cases to determine the ventilation standard of an operating room qualitatively, with regard to particles that are interesting from a bacteriological point av view.

Based on the above as background, the tests described below were conducted with tracer gas (nitrous oxide) and with smoke tests for visualization, in order to establish an overall picture of the situation.

The temperatures and air velocities around the operating table were established before the smoke and tracer gas tests were conducted. The temperatures and velocities were recorded by collecting data digitally from 36 probes positioned in a grid pattern in the room.

Four heat sources (devices), each producing 75 W for a total of 300 W, were used during the tests and placed by the operating table in a standardized arrangement to simulate heat produced by an operating team (see Fig. 1). Heat was also radiated from general lighting fixtures (1000 W) in the ceiling, an operating lamp (120 W) and certain other devices. The operating lamp (diameter 98 cm) was positioned 100 cm over the operating table (190 cm above the floor) during all tests.

The smoke and tracer gas tests were conducted with four heat-producing devices but without human activity and presence, and with two devices and two persons, who remained completely still, moving mainly their arms and hands above the operating table, according to a standardized plan of movements. The smoke tests were documented on video and with still pictures.

During the tests tracer gas, the source for dispersing the gas was placed by the operating table, where the surgeon stands, and the concentrations were recorded at two places by the operating table, and in the exhaust air duct. Fig. 1 shows the positions of the tracer gas source and probes by the operating table.

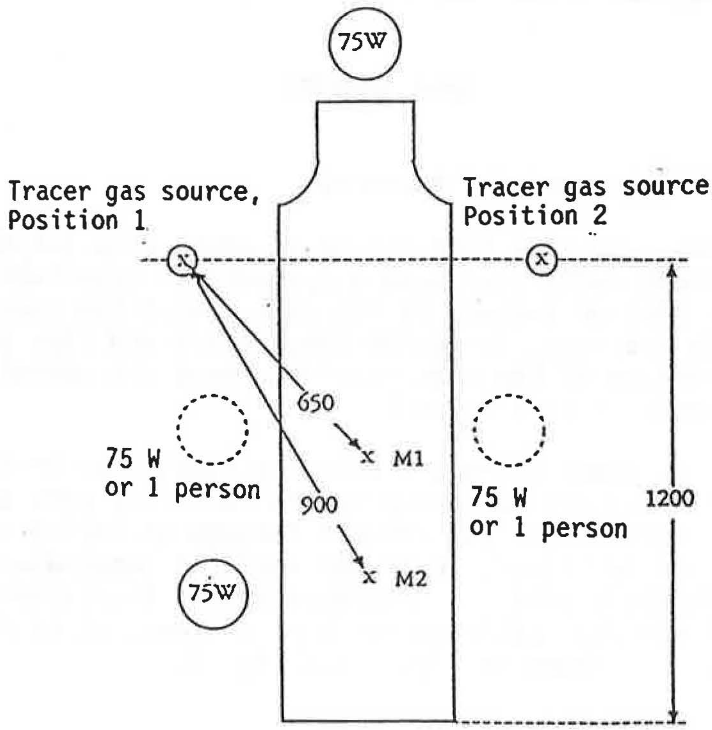

Fig. 1. Placement of the heat-producing devices, persons, sources for distributing traces gas and probes around the operating table.

The precise positions of the devices to disperse tracer gas, and those of the probes, were 10 cm above the operating table, 100 cm above the floor. The tracer gas flow was standardized at 130 l/h.

How the Test Were Conducted

Tests were conducted on three separate occasions (three different phases), with different supply air systems, in the same operating room at the Umeå General Hospital in Umeå, northern Sweden. Phase 1 consisted of experiments with an inclined screen, with air flows of 1875 m^3/h and 820 m^3/h, providing 16 and 7 air changes per hour, respectively. Phase 2 consisted of tests with a displacement system with air volumes of 1980 m^3/h and 930 m^3/h, or 17 and 8 air changes per hour, respectively. The last stage, Phase 3, consisted of tests with a vertical, unidirectional air flow system - a filter ceiling - with an air flow of 9000 m^3/h, of which 7000 m^3/h was recirculated.

During Phase 3, when the filter ceiling was used, the tests were conducted with a lamp (300 W) that had a better aerodynamic design with two small auxiliary lamps, or "satellite lights". In this case, induction tests were also conducted, in which particle measurements were made to investigate the capability of the unidirectional air system to block the dispersal of contaminants. The probes in this test, as in previous experiments, were placed on the operating table (Fig. 1, as in Case 1, M1) and particles were partly generated from a smoke generator (Fig. 1 as in Case 1), and partly from persons present in the room.

In conclusion, it can also be mentioned that the supply air temperature was a few degrees below room temperature in all test cases.

Test Results

Temperature, Velocities and Air Movements

The temperature and flow patterns in an empty room (without activity from people and heat radiation) have a symmetrical structure for the various air distribution systems in the area around the operating table. When heat devices are used, irregular temperature and flow patterns are obtained. The position of the heat devices around the operating table play a decisive role in this respect.

In summary, the temperature and velocity levels for both systems with conventional air flows are definable in the sensitive area around the operating table. When air is distributed through an inclined screen, the air velocities will be higher, while the vertical temperature gradients will be lower, compared with air distributed in a displacement system. The principle of the flow patterns for both systems, at maximum (conventional) air flows, is shown in Fig. 2 and Fig. 3.

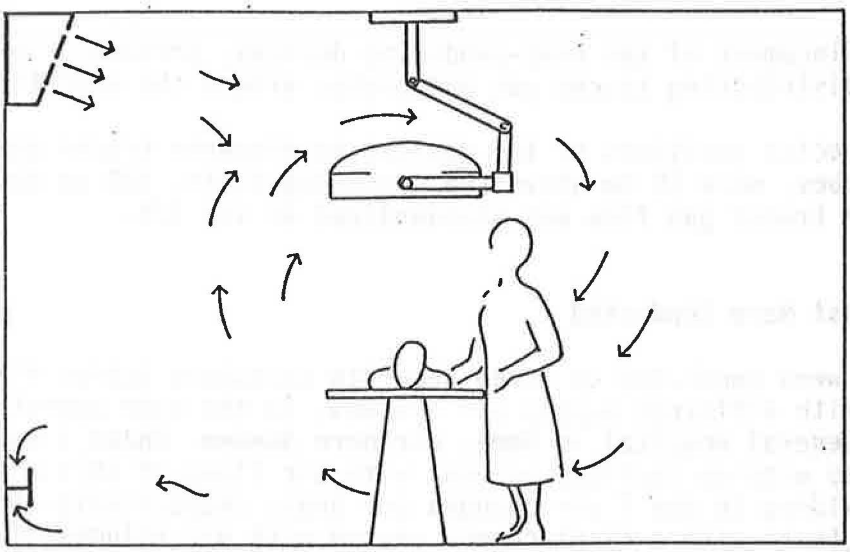

Fig. 2. Observed main flow pattern when air is supplied in the operating room through an inclined screen at 16 changes/h.

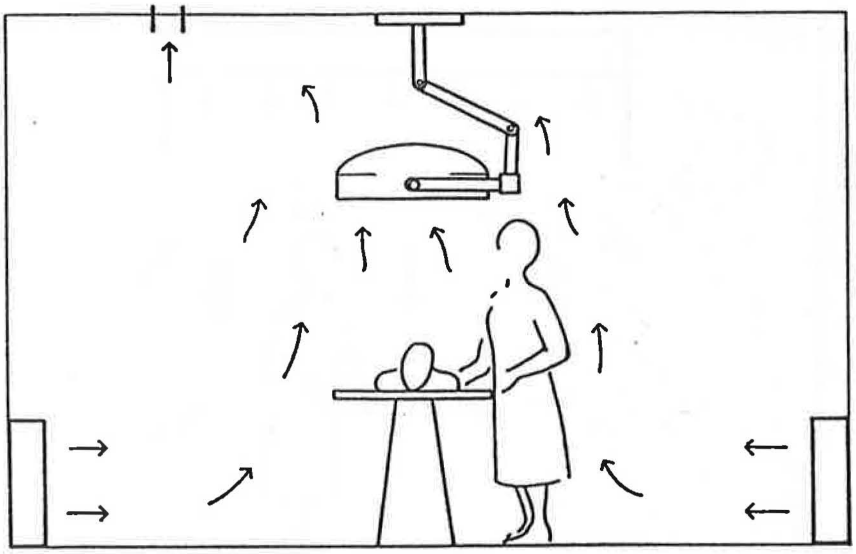

Fig. 3. Observed main flow pattern when air is supplied by a displacement system at 17 changes/h.

Tests were also conducted with both systems at reduced air flow. When air was distributed through an inclined screen, the air jet from the screen does not reach all the way to the operating table. As a result, only a small part of the room is directly ventilated, while the rest of the room is ventilated secondarily. In contrast, when the air is supplied by a displacement system, the air is distributed by the floor and carried up to, and over, the operating table. The recorded air velocities in this case were lower, and the resulting temperature gradients higher, than with the maximum (conventional) air flow.

When air is supplied through the filter ceiling, the air velocity of the unidirectional, vertical flow is approximately 0.35 to 0.40 m/s, resulting in more stable conditions. Fig. 4 shows the principle of the flow pattern for the filter ceiling system.

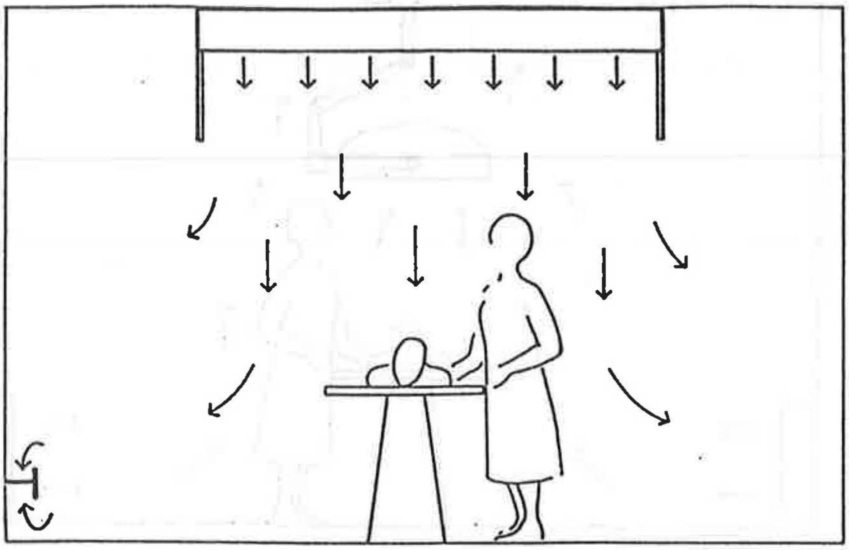

Fig. 4. Observed main flow when air is supplied with the ultraclean system with unidirectional, vertical flow.

To establish an overall picture of the air movements, they were visualized with smoke. The tests were conducted with, and without, persons performing activities. The air flow patterns were recorded on both video and with still pictures.

The smoke tests clearly showed that, compared with the filter ceiling system, both systems with conventional air volumes were more sensitive to disturbances by hand and arm movements from the persons used in the tests.

Tracer Gas Tests - Maximum Air Flow

Tracer gas tests were performed in accordance with the arrangement shown in Fig. 1, in which the gas dispersing source has been placed in both Position 1 and Position 2. The distance between the source and probes was 65 cm and 90 cm, respectively.

Because the air distribution systems have different supply air flows, the recorded tracer gas quantities are shown in dimensionless concentrations for comparison purposes. These are defined as the quotient between measured values and the theoretically calculated concentration value given by the dilution principle. The concentration value of the dilution principle for both systems with conventional flows, based on the previously stated air flows, is 69 ppm when distributed through an inclined screen, and 66 ppm with the displacement system.

For the filter ceiling system with a total air flow of 9000 m^3/h, in which 7000 m^3/h is recirculated, the theoretical concentration value of the dilution principle is calculated on the basis of an outdoor air flow of 2000 m^3/h, to establish a concentration value of 65 ppm. The calculation of the dimensionless concentration has, of course, taken into account the fact that air containing with tracer gas has been recirculated. Thus, the obtained figures in this case can be approximate, although the order of size for the obtained values can be considered correct.

The results of the tracer gas test shown in Table 1 and Table 2.

Table 1. Comparison between different air distribution systems for operating room ventilation in the form of dimensionless concentrations (the quotient between measured values and the value of the dilution principle). The distance between the gas distribution source and probe is 90 and 65 cm, respectively. The position of the dispersal device is the same Position 1 shown in Fig. 1.

	DIMENSIONSLESS CONCENTRATION					
	Without people + 4 x 75 W		2 persons, still + 2 x 75 W		2 persons, moving + 2 x 75 W	
	Dist. 90 cm	Dist. 65 cm	Dist. 90 cm	Dist. 65 cm	Dist. 90 cm	Dist. 65 mm
Inclined screen ($1875\ m^3/h$)	1.1 ± 0.4	1.2 ± 0.4	1.2 ± 0.4	1.2 ± 0.7	1.2 ± 0.4	3.1 ± 1.4
Displ. flow ($1980\ m^3/h$)	0.2 ± 0.1	0.8 ± 0.5	0.3 ± 0.1	0.6 ± 0.4	0.5 ± 0.2	3.0 ± 1.5
Filter ceiling (recirc. $7000\ m^3/h$) (tot. $9000\ m^3/h$)	0.0	~0.02	~ 0.05	~0.10	~0.1	~0.2

Tabel 2. Comparison between different air distribution systems for operating room ventilation in the form of dimensionless concentrations (the quotient between measured values and the value of the dilution principle). The distance between the gas distribution source and probe is 90 and 65 cm, respectively. The position of the dispersal device is the same Position 2 shown in Fig 1.

	DIMENSIONSLESS CONCENTRATION					
	Without people + 4 x 75 W		2 persons, still + 2 x 75 W		2 persons, moving + 2 x 75 W	
	Dist. 90 cm	Dist. 65 cm	Dist. 90 cm	Dist. 65 cm	Dist. 90 cm	Dist. 65 mm
Inclined screen (1875 m^3/h)	4.3 ± 2.9	5.7 ± 4.3	5.0 ± 3.6	1.4 -> 14.0	5.7 ± 4.3	1.4 -> 14.0
Displ. flow (1980 m^3/h)	2.3 ± 1.5	6.1 ± 4.5	3.8 ± 2.3	11.0 ± 5.0	3.0 ± 1.5	9.1 ± 4.5
Filter ceiling (recirc. 7000 m^3/h) (tot. 9000 m^3/h)	~0.10	~0.15	~0.2	~0.2	~0.2	~0.25

It can be noted from Table 1 and Table 2 that there is a great difference between the vertical, unidirectional flow system and the systems bases on conventional air flows. The dimensionless concentrations of the latter systems, with two persons present in the room, are in the range of 5 to 60 times higher than in the filter ceiling system.

The level of the relationship ca be appropriately compared with data from Lidwell et al (15, 17), who have determined the average value of the number of bacteria-carrying particles per cubic meter of air (CFU/m^3) during operation, for both the total mixing and unidirectional air flow systems. The relation between the average value of the total mixing system and vertical, unidirectional flow system will be 17 and 82 with these results, depending on whether or not the unidirectional flow system is equipped without or with vertical side walls. The better values for the filter ceiling system are, of course, due to the system's higher air volume and subsequent, stable air distribution.

When the air distribution system with inclined screen is compared with the displacement system, the latter system frequently has lower (better) values in rooms without human activity, while both systems obtain values in the same range with activity. At Position 2 for the gas distribution source (Table 2), higher concentration values are obtained for both these systems, compared with Position 1 (Table 1). This can be explained by the way the air movements affect the dispersion process. These higher values are due to the fact that a macroscopic room vortex is obtained with the system with inclined screen, while the air distribution of the displacement system is completely dependent on the placement of the heat source, that is, its convection flow.

Tracer Gas Test - Reduced Air Flow

Tracer gas tests were also conducted at a reduced air flow in the system with inclined screen and the displacement system. The tests were basically conducted in accordance with what was reported in connection with Table 1 and Table 2. Based on the previously given air flows, at reduced opeation, the theoretical concentration value of the dilution principle will be 159 ppm, when the air is distributed through an inclined screen, and 140 ppm, with the displacement system.

The results obtained with the recorded concentration values give higher figures than at the maximum air flow. When the air flow is reduced, the systems are more sensitive to disturbances. As a consequence, the maximum value of the infrared analyzer is frequently exceeded in the experiments in which two persons participated, whereby the mean value of the concentration cannot be determined.

In summary, the following applies: when the air flow is reduced, higher concentration values are obtained, regardless of the system that is selected. A large number of additional tests would be required to finally determine which system provides the best conditions from a contamination standpoint, when the air flow is reduced. This outside the scope of these investigations.

Particle Concentration - Filter Ceiling

Induction tests were also conducted with particles to determine the effect of the HEPA filter in the filter ceiling. A smoke generator, in which condensed paraffin oil is formed with an approximate diameter of 1.0 µm, was used as the particle generator in these tests. The particles were released almost impuls-free from Position 1 through a point diffuser in accordance with what was reported in connection with Fig. 1. The distance between the diffuser and probe was 650 mm. Three persons with conventional work clothing were also in the room - no one was wearing operating room clothes.

The recorded particle size were lareger or equal to 0.5 µm, 1.5 µm, 3 µm and 5 µm. The particle concentration in the exhaust air was measured before and after each test series. The average value of these figures was established as the basic level.

In addition to the difference in the positioning of the probe noted above, the tests were completely analogous with those reported for the filter ceiling in connection with Table 1. The obtained particle values are shown in Table 3 in the form of dimensionless particle concentrations by dividing the respective basic level of the particle size.

Table 3. Recorded concentration values shown in the form of dimensionless particle concentrations (quotient between the measured value and the average value in the exhaust air). Three persons were present in the operating room together with the dffuser as in Case 1. The probe was positioned in accordance with M1 (65 cm) as shown in Fig. 1. Air system: Filter ceiling.

	DIMENSIONLESS PARTICLE CONCENTRATION			
	≥ 0.5 μm	≥ 1.5 μm	≥ 3.0 μm	≥ 5.0 μm
Without people 4 x 75 W	~ 0.01	0.01	0.01	0.0
2 persons, still 2 x 75 W	~ 0.01	~0.01	0.015	0.01
2 persons, moving 2 x 75 W	1.2 ± 0.5	1.8 ± 0.9	12.6 ± 8.5	34 ± 32

If the values of the filter ceiling in Table 1 are compared with the levels in Table 3, it can be established that the values for the dimensionless concentrations are constantly far below 1.0 (the theoretical value of the dilution principle) in the case with no person, and with two persons not moving, while with two persons moving, a sharp change occurred during the particle tests. The higher levels in Table 3 with two persons moving is explained by the fact that the movements of the two persons generate particles in the vicinity of the probe. This indicates both the importance of proper operating room clothing and good work discipline.

Conclusions

The test results show that the filter ceiling system clearly provides the best results. A comparison between the air distribution system with inclined screen - the total mixing system - and the displacement system, no decisive difference could be noted from a contamination standpoint, when persons are moving in the operating room. Both systems are rather sensitive to disturbances. People, movements, the radiation of heat and even objects therefore have a decisive impact on the flow pattern and even the transport of contaminants.

Bacteriological tests were conducted at the Umeå General Hospital under the management of Professor Sven Friberg. Since these tests will be described in a separate article, only a few of the test conclusions will be presented here. In accordance with what was described earlier, the results from the bacteriological tests do not show any principal difference between the total mixing and displacement systems. In contrast, a sharp improvement was obtained with the vertical, unidirectional air flow of the filter ceiling system. The relation between the bacteriological values of the two systems with conventional air flows, and those of the filter ceiling, lie in the range of 10 to 70 in the various test cases, which agrees with the relations reported earlier.

References

(1) Carlsson, P., Occupational exposure to anaesthetic gases, doctoral dissertation performed at the Department of Anaesthesiology, Karolinska Institute and the Department of Heat Technology, Royal Institute of Technology, Stockholm, 1984.

(2) Lindkvist, A., Lindkvist, R., Development of elimination technologi at the University of Umeå, University of Umeå Campus Print Shop, Umeå, Sweden, 1987. [ISBN: 91-7174-315-4]. (In Swedish.)

(3) Järmyr, R., The spread of pollutants in different parts of room volume served by displacement ventilation, Proceedings of the ICCCS Symposium in Los Angeles, 1988, 201-203. [ISBN: 0-915414-37-6].

(4) Ljungqvist, B., Öhlund, L., Operating room ventilation, an orientation. Sjukhuset magazine, No. 10, 1983. (In Swedish.)

(5) Andersson, P-A., Hambraeus, A., Zettersten, U., Ljungqvist, B., Neikter, K., Ransjö, U., A comparison between tracer gas and tracer particle techniquies in evaluating the efficiency of ventilation in operating theatres, J. Hyg, Camb., 1983, 91, 509-519.

(6) Andersson, P-A., Hultin, E., Ljungqvist, B., Ventilation in operating rooms - a report from a test series. VVS & Energi magazine 5:1985. (In Swedish).

(7) Blowers, R., Crew, B., Ventilation of operating-theatres, J. Hyg, Camb., 1960, 58, 427-448.

(8) Lidwell, O.M., The evaluation of ventilation, J. Hyg, Camb., 1960, 58, 297-305.

(9) Lidwell, O.M., Williams, R.E.O., The ventilation of operating-theatres, J. Hyg, Camb., 1960, 58, 449-468.

(10) Hambraeus, A., Bengtsson, S., Laurell, G., Bacterial contamination in a modern operating suite. Effect of ventilation on airborne bacteria and transfer of airborne particles, J. Hyg, Camb., 1977, 79, 121-131.

(11) Charneley, J., Eftekhar, N., Postoperative infection in total prosthetic replacement arthroplasty of the hip-joint, with special reference to the bacterial content of the air in the operating room, British Journal of Surgery, 1969, 56, 641-649.

(12) Charnley, J., Postoperative infection after total hip replacement with special reference to air contamination in the opeating room, Clinical Orthopaedics, 1972, 87, 167-187.

(13) Whyte, W., Shaw, B.H., Barnes, R., A bacteriological evaluation of laminar-flow systems for orthopaedic surgery. J. Hyg, Camb., 1973, 71, 559-564.

(14) Lindberg, L., Operating rooms, an overview of new research findings and practical results. Läkartidningen magazine, Vol. 76, No. 12, 1979. (In Swedish.)

(15) Lidwell, O.M., Lowbury, E.J.L., Whyte, W., Blowers, R., Stanley, S.J., Lowe, D., Effect of ultrclean air in operation rooms on deep sepsis in the joint after total hip or knee replacement; a randomised study, British Medical Journal, 1982, 285, 10-14.

(16) Ljungqvist, B., Some observations on the interaction between air movements and the dispersion of pollution, Swedish Council for Building Research, D8, 1979. [ISBN: 91-540-3055-2].

(17) Lidwell, O.M., Air, antibiotics and sepsis in replacement joints, Journal of Hospital Infection, 1988, 11, 18-40.

SUMMARY

In view of the discussions during the past few years about the ability of ventilation systems to remove airborne contaminants in opeating rooms, the authors participated in full-scale tests in connection with the re-building and expansion of operating rooms at the Umeå General Hospital in Umeå, Sweden. The full-scale tests aimed to investigate the characteristics of various air distribution principles, in which supply air systems based on total mixing ventilation, displacement ventilation and a downward, unidirectional air flow ("ultraclean air system") were studied. From the standpoint of contamination, the results showed that the system with downward unidirectional flow, with its larger air flow, performed the best. When the total mixing system was compared with the displacement system, no decisive difference could be noted, since there were persons active in the room.