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Citation for published version (APA):

DOI:
10.1016/j.buildenv.2011.06.015

Document status and date:
Published: 01/01/2011

Document Version:
Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:
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Download date: 29. Aug. 2023
Testing the effectiveness of operating room ventilation with regard to removal of airborne bacteria

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Abstract

In this research the ability of the ventilation system in an operating room to keep the operating table and the instrument tables free from airborne bacteria has been evaluated in an experimental mock-up for different ventilation systems under various static circumstances. To accomplish this, the VDI 2167 particle test has been used as a basis. In this test particles are released on the floor and smoke concentrations are measured on the operating table.

The VDI 2167 method was able to distinguish the different systems, but did not provide for a complete evaluation. The thermal balance in the room plays a major role in whether a laminar downflow system works and the VDI method does not incorporate this into the tests in an adequate manner. Moreover, the influence of surgical lighting is not included in the test method in an effective way.

Keywords

OR, ventilation, measurements, LAF-system.

1 Introduction

Airborne bacteria in operating rooms can cause infections deep in the wound. The most critical areas in an operating room are the operating wound and the instrument tables. A better ventilation system reduces the concentration of bacteria, and therefore the chance of deposition of bacteria in the wound [1]. There are two types of systems in use; laminar and mixing systems. With mixing systems, the concentration of contaminants is diluted. A higher ventilation or recirculation rate automatically gives a lower contaminant concentration. Laminar systems on the other hand are supposed to deliver clean air to critical areas before it mixes with contaminated surrounding air.
Laminar downflow systems are seen as the successor of mixing systems, but research that correlates postoperative wound infections and the type of ventilation system in use has not shown consistently that laminar airflow systems lead to fewer infections than mixing systems [2-6]. From this it can be concluded that either the airborne route does not play a significant role in the occurrence of wound infections or laminar flow systems do not perform in practice the way they should.

The performance of ventilation systems was evaluated by various different people over the past years, with different outcomes. One method to measure the performance is either to use Petri dishes to sample deposition of bacteria during an operation, or to use a bacterial air sampler to measure the concentration of airborne bacteria [7-9]. This is a very direct way to evaluate risk, but because factors such as quality of clothing and procedures influence the result, this method is unsuited for comparison between systems in different hospitals.

Alternatively the transport of bacteria can be simulated using either a fixed particle source or a tracer gas when the operating theatre is not in use. The advantage is that the source strength in these cases is fixed, so that any change in measured concentration is due to changes of the performance of the ventilation system. This method has been used by [10-12]. A standardized method is described in VDI 2167 [13] and was later incorporated in DIN1946-4 [14]. A fixed source allows measurement of the performance of the ventilation system directly. If measuring is impossible or impractical, it is also possible to do a simulation instead. [15-18]

The VDI 2167 describes a way to test whether particles from the environment are able to penetrate the clean area and settle in the operating area. To perform an assessment according to VDI 2167, heated puppets have to be placed in the room.
Smoke sources are placed on the floor around the clean area. By measuring the smoke concentration on the operating table the performance of the ventilation system can be measured. Because lamp position, puppets, equipment, particle source position and particle measurements have all been standardised, it is possible to compare results from tests in different rooms.

The main question in this paper is whether the VDI 2167 is able to differentiate between different types of ventilation systems. It also evaluates the influence of the way a room is used on the performance of the ventilation system.

2 Method

To evaluate the VDI 2167 method, measurements have been performed in a full scale operating room mock-up with three different ventilation systems. Subsequently, variations have been made to the use of the room to investigate the influence of these changes on the measured performance. These variations are a changing internal heat load, addition of instrument tables, different surgical lights and a change in the ventilation exhaust. The particle measurements have been performed according to the VDI 2167. In addition to particle measurements on the operating table, particle concentrations on the instrument tables have been determined to investigate whether the protection changes here.

2.1 Test chamber

The room where the measurements have been performed is 6 x 6 metres and 3 metres high, which is normal for an operating room. A picture of the room can be found in figure 1. The air was supplied through 4 separate plenums in the ceiling and extracted through 12 grilles in the corners of the room. Details can be found in appendix A. With the three large plenums it was possible to mix recirculated and fresh pre-cooled air in any ratio. In this manner the velocity and temperature of
these plenums could be changed freely. The small plenum only supplies recirculated air, as it is usually meant to keep the anaesthetist warm. Therefore, on this plenum, only the flow could be regulated.

An operating table was placed underneath the middle of the central plenum and 6 puppets were placed around it, according to the VDI 2167. Smoke was made using a generator that creates a constant stream of particles. There were 6 release points for this smoke on the floor. Smoke concentrations were measured on three points on the operating table and on each of the instrument tables present. This allowed studying the transport mechanism from the surrounding area into the clean area.

2.2 Experiments
Three different systems have been examined under various circumstances. For these systems, changes have been made to the use of the room. Between experiments only one aspect has been changed. The experiments can be found in table 1.

In the first experiment the setup in the room was kept exactly the same, but the velocities and temperatures of the different plenums were changed. The systems are:

- A uniform plenum with an inlet velocity of 0.33 m/s and temperature of 22 °C.
- A system where the temperature from the middle plenum is 18.6 °C and side plenums 20.9 °C.
• A system where the temperature is the same, but the velocity of the middle plenum is 0.34 m/s and the velocity of the side plenums is reduced 0.17 m/s.

The system with different velocities was not properly produced. As the middle diffuser was fed from one side, it was not able to produce a uniform velocity distribution for the increased amount of air. The distribution of the velocity for this case can be found in figure 3.

In the second experiment the air exhaust system was altered. The top exhaust grille in each corner was closed, thereby increasing the amount of air exhausted through the bottom grilles. This resulted in 45% of the air being extracted from the bottom grilles, and 55% through the middle grilles. This experiment was performed with an internal heat load of 900 W and no additional instrument tables present. The inlet plenum had a uniform velocity profile of 0.25 m/s and a temperature from the central plenum was 1.2 °C colder than the side plenums. In this experiment particles were released on their outside positions.

In the third experiment a plenum with a uniform temperature was used. Puppets were placed around the table normally, and the open lamp shape was used. The difference between the two situations was an additional heat load of 1600 W in the form of two convector units, each producing 800 W. The convector units were placed on one side of the bed, 1 meter from the wall. The average inlet velocity of the plenum was 0.33 m/s for the case with a heat load of 900 W. It was 0.34 m/s for the case with 2500 W heat load. In both cases the temperature from the side plenums was measured 0.1 °C lower than the middle plenum.
In the fourth experiment instrument tables are placed in the room. The system is set up to produce equal velocities, but a lower temperature at the middle plenum. The internal heat load is varied from 900 W to 4500 W, again using convector heaters for the additional heat production. The particle concentration was measured on the operating table as well as on the instrument tables. The instrument tables were placed behind the puppets, directly underneath the side plenums. The heaters were placed between the instrument tables and the side wall. Because of this, the smoke sources could not be placed in the usual places, and were positioned further away from the operating area.

In the last experiment different lamp shapes were used, again with a system with temperature difference, but no difference in flow velocities between the inlets was used. The three different lamp shapes had an open shape, a semi-open shape and a closed shape. These are the same shapes as used in [19]. The different lamp shapes were measured with particle sources outside the operating area exclusively. The system used was a multiple temperatures system.

2.3 Performed measurements

The measurements performed for each case can be divided into determination of the boundary conditions and testing the performance of the room. Measurements of the boundary conditions were

- The air velocity was measured 15 cm underneath the plenums to check the uniformity of the velocity (8 evenly distributed positions under each of the large plenums and 4 positions under the small plenum).
- The flow rate through each of the 12 ventilation discharge grilles.
- Infrared photographs were made of the room walls to record boundary conditions.
• If equipment was on, the amount of electrical energy used by these was measured.

To test the performance of the ventilation systems the method described in the VDI 2167 is used. Smoke sources are placed on the floor in the vicinity of the operating area. Smoke concentrations on the operating table and on the instrument tables are determined using a particle counter. To determine the source strength, the particle concentrations on all inlets and outlets were measured.

During the smoke measurements temperature measurements were conducted in the room as well. One probe was placed underneath each plenum to monitor the inlet temperature. The temperature gradient in the room was measured by suspending 6 temperature probes on a string from the ceiling.

Particle measurements start with a 4 minute delay to let the airflow pattern recover after the particle counter has been repositioned. After that, four measurements of 4 minutes each were run consecutively. In the results the minimum and maximum average values of these 4 measurements are indicated in the error bars.

Particles were generated using a liquid particle generator PALAS AGF 2.0 IP and measured using a Lighthouse Solair 1100+ particle counter. The size brackets measured are indicated in figure 2.

To determine the source strength, the concentration was measured at each of the 12 exhausts during a period of 16 minutes. The concentration directly underneath each plenum was measured as well. Results of average particle concentration
measurements can be found in figure 2. The largest concentration of particles generated is in the size range between 0.5 and 1.0 \( \mu m \). For this reason, and because these particles are the same size as small bacteria, the size range between 0.5 and 1.0 \( \mu m \) was used in the calculations of the performance of the ventilation system.

2.4 Calculation of the protection factor

As the filters used did not prevent all recirculation of particles, the calculation of the protection factor needs an additional term. In the VDI-2167 calculation, the protection factor is calculated by dividing the measured concentration by the concentration in a fully mixed case.

As the clean supply air is contaminated with non-clean air, this has to be taken into account when calculating the ratio between the two. The equation used for this compensation can be found in equation 1.

\[
PF = -10 \log \left( \frac{C_p - C_{in}}{C_{out} - C_{in}} \right)
\]  

(1)

\( C_{out} \) is the flow rate weighted average concentration at exits
\( C_{in} \) is the concentration at inlet directly above measurement point
\( C_p \) is the actual measured concentration

Assumptions made here are that clean air comes from the plenum directly above measurement spot. By treating the average outflow concentration as source, it is implicitly assumed that a negligible portion of particles deposit on surfaces or merge. [20]
2.5 Accuracy of the determined protection factor

Each measurement was repeated 4 times. The error bars in the graphs in the result section represent the lowest and highest protection value measured. As these measurements were performed right after each other, fluctuations in boundary conditions in the room during the day are not included in this error estimation.

To estimate the variation during the day, particle measurements on one instrument table performed as first measurement of the day was repeated as last measurement of the day. In the morning the protection factor between 0.25 and 0.29 was measured. In the afternoon it was between 0.37 and 0.45. Variations during the day therefore add a variation of \( \pm 0.13 \) in the protection factor.

Besides this variation due to external influences during the day, there were variations in boundary conditions between different tests. Values of measured boundary conditions for all experiments can be found in appendix B. The influence of systematic errors such as accuracy in positioning the measurement probe, the instrument tables or the puppets or slight variations in boundary conditions on the measured particle concentration can not be estimated from these measurements as the gradient of particle concentrations can be very steep.

3 Results

3.1 Experiment 1: Different systems

Figure 4 shows that, with a relatively low heat load, the multi-temperature plenum behaves most consistently. There is almost no variation between different
measurement runs. The uniform plenum has low protection near the foot of the operating table and the multiple air velocity system has low performance near the head of the operating table.

3.2 Experiment 2: Location of the exhaust
The location of the exhaust does not influence the measured protection factor. As can be seen in figure 5, the temperature in the periphery of the room is higher if all air leaves in the lower and middle corners.

3.3 Experiment 3: Different heat loads with a uniform plenum
The protection factor near the foot of the table is reduced when only a few heat sources are introduced. If internal heat gains rise further, the temperature in the periphery rises and the airflow is no longer disturbed. The temperature difference between the environment and the mean inlet temperature rises from 0.3 °C to 0.5 °C when the heat load is increased from 900 W to 2500 W. Protection factors can be found in figure 6 and the temperature gradients in figure 7.

3.4 Experiment 4: Different heat load and instrument tables
Introducing a large heat load in the room lowers the performance of the ventilation system on the operating table as well as on the instrument tables. The temperature difference between the mean inlet temperature and the environment rises from 0.5 °C to 2 °C when the internal heat load is increased. In the high heat load case the gradient is very steep above the highest outflow grille. Protection factors can be found in figure 8 and temperature gradients in figure 9.

3.5 Experiment 5: Different lamp shapes
In this case, no differences in protection factor were measured between open, semi-open and closed lamp shapes. Values are identical to the temperature difference case in experiment 1. Temperature gradients show a difference between 0.5 and 0.8 °C between mean inlet temperature and periphery. Variations can be attributed to slightly altered boundary conditions.

Measurement results of the boundary conditions can be found in appendix B.

4 Discussion

The imperfect filters in the supply air made it impossible to distinguish protection factors over 2.3. Some experiments produced considerably lower protection factors. These can be seen as an indication of a disturbance of the downflow.

Repeating the experiment 4 times gives not only an indication of accuracy of the measurement, but also of the stability of the situation. When one of the experiments was repeated at the end of the day it showed a deviation of 0.13 from the early morning, so no large variations are to be expected.

Experiment 1, the comparison of the different systems, is performed with a low internal heat production. The uniform plenum does not perform well near the foot of the operating table. The system that uses a temperature difference performs fairly well on all positions. The variations between the different measurements were also low, indicating a stable situation.

In the case where it was attempted to create a velocity profile, the velocity near the head of the patient was significantly higher. Despite of the increased amount of air the protection is lower near the head of the patient. It must be stressed that
the velocity profile was not produced accurately because of limitations in the system. Therefore no general conclusions can be drawn about this system.

Changing the exhaust from its normal distribution to an exhaust at the bottom two grilles did not change the performance of the ventilation system. The case reviewed here has an internal heat load of only $900\, \text{W}$. Temperature gradient measurements show that the temperature near the side wall does increase somewhat, especially between the top and lower grille. Experiments 3 and 4 show that the temperature distribution in the room can play a significant role. With a higher internal heat load the position of the exhaust can be expected to play a more significant role in the performance of the ventilation system.

In experiment 3 the air flows down properly either with no heat sources present or with an internal heat load of $4500\, \text{W}$. Introducing relatively small heat sources directly underneath the plenum disturbs the downward airflow. The measurement point near the feet of a patient is closest to the edge of the plenum and therefore more particles are measured there. A larger internal heat load, partially outside the clean area creates a temperature gradient that helps the air to flow down, negating the effect of the local disturbances. This means that it is necessary to use heated puppets to test the performance of OR ventilation.

The other conclusion is that, in this case, it does not matter where the particle sources are located. The change in particle concentration therefore originates from the outside.
In experiment 4 with a 900 W heat load in the room, the instrument tables on the lamp side performed worse than the ones on the other side of the operating table. Especially the one near the head of the plenum was affected. This can be the result of the lamp itself, but also of the proximity to the 300 W puppet to this instrument table.

When the internal heat load is increased to 4500 W, the quality of the ventilation on all points decreases. The largest change here is on the instrument tables. Measurements using the VDI 2167 do not take into account that a significant heat load is present in the room and does not require measurements on the instrument tables. Therefore this problem will not arise during a standard evaluation procedure.

The different operating lamp shapes did not affect the particle concentration on the operating table in a significant way. The lamps have been placed according to the VDI procedure, which is behind the head of the surgeon. In this position it clearly does not make a difference what lamp is in use. Zoon [19] argues that the lamp shape should make a difference, and Chow [15] draws the conclusion that the lamp position makes a difference. Placement of the lamp in the procedure should be reconsidered if it is not in agreement with practice.

The performance difference for the various designs of ventilation systems can be large, especially when the variations considered here are taken into account. In all cases the protection was better than with a mixing system, but the examined circumstances are still somewhat idealised. First of all, no movement was simulated in the OR. Brohus [16] found that this has some influence on the particle
distribution. This could contribute as well, especially in cases where the downflow area is relatively unstable.

From experiments 3 and 4 it follows that internal heat load in the room plays a significant role in the performance of the system. Experiment 2 shows that the temperature gradient in the room can be altered significantly by the place where air is extracted. The temperature near the ceiling in the high internal heat load cases confirms this. This suggests that the temperature gradient in the room can be altered by changing the ratio of air extracted from top and bottom of the room and that such a system would improve cleanliness of the instrument tables.

5 Conclusions

The laminar flow systems tested always performed better than mixing systems with the same ventilation rate. There was however a large variation in the performance of the different systems, especially when assessed on the instrument tables. The VDI method was able to distinguish between the performance of different systems, but some important aspects are not included. Variations in usage, resulting in different internal heat loads are not prescribed in the VDI 2167, but play an important role in the performance of the system. Due to its prescribed position, the influence of the operating lamp as an obstruction is not evaluated in this procedure. As some systems might be more vulnerable than others to these variations, they need to be evaluated to determine the robustness of a system.

The temperature distribution in the room plays a significant role in the performance of the system and the thermal balance can be altered significantly by the place where air is extracted.
One use of the VDI method could be to evaluate the ventilation system in combination with infection incidence in order to create a better correlation of the influence of the ventilation system and infection incidence. For this type of research it can be recommended to alter the VDI procedure to match the use of the room during surgery.

6 Acknowledgement

We would like to thank Interflow/BAM Techniek BV for generously lending us their operating room for a month, Merford Klimaattechniek BV for supplying an operating lamp, Stichting Promotieonderzoek in de installatietechniek and Deerns consulting engineers for financing the research.

7 Literature


prophylaxis systemically and in bone cement on the revision rate of 22,170 primary hip replacements followed 0-14 years in the Norwegian Arthroplasty Register”, Acta Orthopaedica vol. 74, No. 6, Pages 644-651, DOI 10.1080/00016470310018135


Appendix A : Details of the measurement setup

In this appendix the details of all measurements are summarized.

The room measured 6x6x3 meters. The floor was made of wood and raised from the standard concrete industrial hall by use of wooden beams. The walls and ceiling were insulated on the outside. Infrared photos, compared to air temperatures near the wall showed that the walls can be considered adiabatic. Figure A.1 shows the measurement setup for all cases without instrument tables, and figure A.2 for the cases where instrument tables were used. Table A.1 shows the size of the inlet plenums.
Appendix B: Boundary conditions

The return air goes through 12 grilles, 3 in each corner of the room. The square grilles measured 496 mm on each side and were located above each other, with a distance centre to floor 448 mm, 994 mm and 2086 mm. As the grilles were connected to a duct with a fixed valve, the ratio of exhaust air was measured as 42%±1%, 32%±1% and 26%±1% through the top, middle and bottom grilles respectively. Inlet boundary conditions for all plenums can be found in table B.1.

Figure 1. Test chamber in which the measurements were performed.

Figure 2. Volume averaged particle concentrations in the supply and exhaust air of the room.
Figure 3. Inlet velocities (m/s) in the velocity difference case.

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Figure 4. Performance of the different plenum configurations with 900 W internal heat load and particles released on the outside.

![Bar chart showing performance with different configurations]
Figure 5. Temperature gradient in the room with two different exhaust configurations

Figure 6. Performance of the uniform plenum with low and moderate internal heat load. Error bars indicate minimum and maximum of the 4 measurements.
Figure 7. Temperature gradients in the room with a uniform plenum and different heat loads. Temperature in the isothermal case is not measured.

Figure 8. Performance of the ventilation system on the operating table and on the instrument tables for two cases with different heat loads.
Figure 9. Temperature gradients in the room with a multi temperature system and instrument tables present for two cases with different heat loads.

Figure A.1. Floor plan of the experimental setup without instrument tables.
Figure A.2. Floor plan of the experimental setup when instrument tables were included.
Table 1. The different test setups

<table>
<thead>
<tr>
<th>test</th>
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<td>Different systems</td>
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<td>2</td>
<td>Location of the exhaust</td>
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<td>3</td>
<td>Different heat loads with a uniform plenum</td>
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<td>4</td>
<td>Different heat load and instrument tables multi temperature plenum</td>
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<td>5</td>
<td>Different lamp shapes</td>
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Table A.1. Dimensions of the different plenums.

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