Investigation of methods regarding the effectiveness of ventilation strategies in an operating room on the removal of airborne germs using tracer particles

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Abstract. In this study contaminant distribution in an operating room is evaluated experimentally to be able to compare different ventilation concepts afterwards. Low-turbulent unidirectional ventilation (LAF) is used in this study. Heated dummies are positioned around the operating table, which release tracer particles that surrogate airborne germs and measured in critical areas for bacteria spread. Measurement results are evaluated and compared in terms of the degree of protection as well as the local air quality index. It is shown that realistic arrangements limit the usage of the degree of protection. Also, low local air quality indices show recirculation areas appearing at the operating table.

1 Introduction

Surgical-Site infections (SSI) are often a cause of prolonged healing, inflammation and, unfortunately, a common cause of death globally [1]. The spread of airborne contamination plays a critical role in protecting against SSI [2]. Therefore, evaluating the effectiveness of ventilation is very important for the classification of operating rooms (ORs).

Especially the spread of bacteria is crucial here, as viruses and fungal spores are less likely to cause SSI in the OR [3]. Monitoring these airborne bacteria is not trivial, as they mostly occur connected to a carrier medium. More precise, the transport is based on the spread of saliva droplets and skin flakes. An important source of these is the surgical staff. Saliva droplets can have different sizes. In pure breathing, the particles are usually small, since most of them are formed in the lungs. However, since speaking, shouting and singing are also respiratory activities occurring during operations, the particles can be formed in the voice-producing areas, i.e. the larynx and the oral cavity. Thus, a trimodal distribution of particle size occurs in respiratory aerosol, in a size range between 0.1 – 100 µm [4]. Very large droplets > 10 µm should be retained by the mouth-nose protection worn [5]. Since the germs responsible for SSI, often S. aureus, have a size of > 1 µm, and are airborne dissolved in larger particles, it can be assumed that the particle sizes to be investigated are in the range of 1-20 µm as it was already derived in [6].

This results in the monitoring problem described at the beginning: particles > 2 µm do not behave ideally airborne as the particle diameter increases [7]. Those particles sediment rapidly and show increasingly poor following behavior relative to the streamlines of the air.

In conclusion, measuring the concentration of germs in the exhaust air might not be representative for the concentration of airborne germs at the operating table (OT). Instead of using air samplers, particles > 10 µm are usually collected using sedimentation plates or water-sensitive paper, and their size is estimated depending on the distance from the source [4].

A methodology will now be demonstrated in order to investigate the status quo of current ventilation technology in a research-OR. For this purpose, an appropriate aerosol is generated in this size range. The corresponding methodology for aerosol generation is listed in the previous publication [6]. The particles are emitted at thermal person simulators. The particles will be counted at crucial locations with decentralized remote laser particle counters.

At the OT, a statement will be made about the concentration of airborne particles in order to make a statement for the concentration of airborne CFU above the wound field. The local air quality index (ε₃₅) is determined as an evaluation variable, as a ratio of the particle emission of the particle generators and the number of particles at the sampling points. Also, according to the German standard, the “degree of protection” is calculated and compared for differing arrangements.

2 Methods

The research OR at the Hermann-Rietschel Institute can be ventilated with various flow regimes. In any case, the room is ventilated with a slight overpressure to the surrounding hall. The LAF unit has a size of 3.20 m x 3.20 m and is composed of ceiling panel with terminal filters and laminizer fabric. The extract air (ETA) is discharged through wall outlets in all four corners of the...
The dummies are heated, adjusted to the activity level of each OR staff member. The staff simulators are dressed according to real OR staff with disposable gloves, gown, face mask and hood. The patient simulator is made of Styrofoam, has a girth of 59 cm and a length of 1.60 m and is heated at the top. More information about the person simulators is given in [8].

As surgical lamps (SL) generic spherical SL with a sensible heat load of 35 W per SL were used. The SL are posed diagonal and the base is inclined perpendicular to the patient's wound area, as shown in Fig. 1.

In this investigation, the initially described airborne CFUs are surrogated by tracer particles [6], as these are easier to apply experimentally. The aerosol generators are attached to the person simulator at the height of the chest. There are four aerosol generators with calibrated source strength. For each test configuration these are attached to each person simulator in a circulating order. Thus, for each test case, four measurements are performed. Since the particle emission rate is not steady, the count at the measuring points has to be integrated for each measuring point \( N_{x,i} \) over the measurement time \( t \) to examine the contamination of the defined protected areas.

In order to measure the particles, particle counters type LDPC P0 5-10 (Briem Steuerungstechnik GmbH, Nürtingen, Germany) are used. These count particles in the sizes > 0.5 µm, > 1.0 µm, > 5 µm and > 10 µm, with a coincidence limit of 35 000 000 m\(^{-3}\). This was not exceeded at any time. A zero measurement is performed before starting each measurement. The LDPC sampling flow rate is 1 cfm, the parameters are 60 s sampling time and 1 s purge time. The LDPC are placed in the middle of the OT, IT and AIT. In this study, only the results for the OT are evaluated.

The local air quality index \( \varepsilon^c_p \) is to be used as the evaluation variable. This is calculated according to (1):

\[
\varepsilon^c_p = \frac{c_{exit}}{c_x} \tag{1}
\]

\( c_{exit} \) as a reference concentration is the concentration in the exhaust air, \( c_x \) is the concentration at the position inside the room.

Since the outlet concentration \( c_{exit} \) for particles > 1 µm is a poor reference quantity due to increasing sedimentation, an alternative reference concentration is defined instead using the number of particles emitted in total by the aerosol generator known from [6].

Therefore, mixing a fixed number of particles into the room air leads to an estimated particle concentration in the exhaust air that can be calculated with formula (2):

\[
\varepsilon_{exit} = \frac{N_{ref}}{Q_{exit}t} \tag{2}
\]

Here, \( \varepsilon_{exit} \) is the concentration at the exit, with an ideal mixing of the airflow and particles assumed. \( N_{ref} \) is the number of particles emitted, \( Q_{exit} \) the volume flow of exhaust air and \( t \) is the measurement time. This corrects the error made due to particles that deposit inside the room. The concentration at the sampling probe is known to be calculated by (3).

\[
\varepsilon_{x,i} = \frac{N_{x,i}}{Q_{probe}t_{probe}} \tag{3}
\]

\( \varepsilon_{x,i} \) are the certain concentrations at the sampling probe during the measurement, \( N_{x,i} \) is the amount particles counted per interval. \( Q_{probe} \) is the sampling flow rate, \( t_{probe} \) the sampling interval. However, since the particle emission rate \( N_x \) is not constant during the measurement, \( \varepsilon_{x,i} \) and \( \varepsilon_{ref,i} \), respectively, cannot be used here. Instead, the integral of the counted particles is formed, because the number of particles emitted is fixed by the measurement boundaries (4):

\[
\varepsilon_x = \int \varepsilon_{x,i} \frac{N_{x,i}}{Q_{probe}t_{probe}} \, dt = \Sigma_{i=1}^t \frac{N_{x,i}}{Q_{probe}t_{probe,i}} \tag{4}
\]

\( \varepsilon_x \) describes the particle concentration, \( t_{probe,i} \) the time of each counting interval. This leads to the calculation of the particle concentration at the sampling probe to (5).

\[
\varepsilon_x = \frac{N_{x1} + N_{x2} + \ldots + N_{x,t}}{Q_{probe}t} = \frac{N_x}{Q_{probe}t} \tag{5}
\]

When entering the room to initialize the measurement, particles are introduced into the room. Therefore, a correction factor \( A \), that is introduced by the particles detected from entering the room, is used, to subtract them from the total particle count \( N_x \). Finally, the following equation (6) is obtained:

\[
\varepsilon^c_p = \frac{\varepsilon_{exit}}{\varepsilon_x} = \frac{N_{ref} N_{probe}}{(N_x - A) Q_{room}} \tag{6}
\]
Within the German standard DIN 1946-4 [9], the assessment parameter „degree of protection“ is defined. It can be calculated by equation (7).

\[
SG_E = -\log \left( \frac{c}{c_{ref}} \right)
\]  

(7)

While calculating this reference concentration \(c_{ref}\), the emission rate of the particle source is divided by the inlet volume flow according to (8):

\[
c_{ref} = \frac{Q_{ref}}{A_{ref} \cdot v_{ref}}
\]  

(8)

Here, \(Q_{ref}\) is the particle emission rate, \(v_{ref}\) is the supply air velocity of 0.3 m s\(^{-1}\) and \(A_{ref}\) a ceiling field with the size of 3.2 x 3.2 m\(^2\), which leads to an inlet volume flow of 11,060 m\(^3\) h\(^{-1}\). Also, the assumption of an ideal mix of the particles and the inlet air is made in (8). The most decisive difference between the setup in the standard to the measurement setup shown is the usage of cylindrical dummies instead of realistic person simulators. In both cases, the patient dummy with heated surface was also located on the table.

The measurement setup for the reference measurements is listed accordingly in the standard and is therefore not explained additionally here.

3 Results

The results shall be discussed exemplary now. First, the course of the particle concentration during the measurement shall be displayed in Fig. 2. Here, the particle count is not stationary, especially for larger particles. Also, for particles > 10 \(\mu m\), the count is often below 100 \(\mu m\), which leads to a higher statistical uncertainty. Therefore, the evaluation is done for the overall measurements.

![Fig. 2. Cumulative particle count for an exemplary measurement with realistic arrangement for different particle sizes at the OT, logarithmic scale.](https://example.com/cumulative_particle_count)

Therefore, a comparison between the two cases with larger particles considering \(\xi_p\) (see Fig. 3) as well as a comparison between the position of the aerosol outlet (see Fig. 4) was made. While conducting the measurements for the degree of protection according to the German standard, the values were around 5.5 (\(\xi_p = 316,228\)) without SL and 1.0 (\(\xi_p = 10\)) with the SL at the OT. The generic round SL seems to be not optimal for a real OR. However, regarding the results with the same setup but the measurement with larger particles, attached to the dummies instead at the floor in the periphery area, the results differ. At the OR-table, the results for the degree of protection are - 0.17 (Particle size: 1.0 – 5.0 \(\mu m\)), - 0.14 (Particle size: 5.0-10.0 \(\mu m\)) and 0.47 (Particle size: > 10 \(\mu m\)). The means of the corresponding local air quality indices, sorted by increasing size class, are 0.34, 0.37 and 1.5. This shows clearly that there is a high impact of the position of the source of contamination. Also, larger particles > 10 \(\mu m\) seem to lead to stay inside the recirculating area for a shorter period than smaller particles.

At last, the results for the configuration with realistic person simulators shall be discussed: The degrees of protection are in order of ascending size class – 1.12, - 0.56 and 2.96. The corresponding \(\xi_p\) in the same order are in mean 0.08, 0.18 and 0.64. It can be concluded that the geometry of the operating personnel has a big impact on the emergence of recirculating areas. The high value for \(\xi_p\) for larger particles might be connected to the distance between the particle sources at the anesthetist and the scrub nurse to the position of the sampling probe. Also, due to the smaller girth of the realistic person simulators, the aerosol generators at the OT had a slightly higher distance to the sampling probe.

4 Discussion

It is important to mention here that for the determination of the reference concentration not the volume flow that is used, but always the volume flow of 11,060 m\(^3\) h\(^{-1}\). However, this contradicts the assumption of an ideal
mixed ventilation, as it naturally does not occur with an LAF. Moreover, the most decisive difference between degree of protection and $\varepsilon_{pc}$ is that degree of protection is only related to the particle emission rate, whereas $\varepsilon_{pc}$ is connected to the exhaust concentration. In the standard, it is stated that degree of protection is therefore an assessment parameter that is independent from the inlet volume flow. However, $\varepsilon_{pc}$ allows a comparison between different types of ventilation and geometries.

It would also be conceivable to derive additional conclusions: Since the particle emission rate and the air particle concentration at the sampling points are known, statements could be made about the actual health risks arising from airborne germs. The airborne particle concentration could be connected to the concentration of airborne CRU in a real OR due to the similar physical properties of the particles to airborne CFU. For this, a typical source strength of germs would have to be estimated by a literature review.

Regarding the estimation of a possible risk of infection, the deposition rate of the germs also must be known. The flow velocity and the turbulence intensity at the wound area play an important role here [10], the duration of surgery could be used to estimate a quantity of germs that enter the wound field via the air during surgery. Thus, the exogenous factors can be quantified. But these exogenous factors show other dependencies, e.g. the particle emission rate of the surgical staff depends on their metabolic rate and overall behavior.

Moreover, to finally calculate a risk of infection, the endogenous variables must also be determined. Here, the dose necessary for the occurrence of an infection must be determined. This depends on several individual characteristics of the patient, including the patient's age, possible immunosuppression, other concomitant diseases, obesity and whether the patient is a smoker. Another factor for SSI, for which ventilation again plays a major role, is the risk of hypothermia. High flow velocities in particular promote cooling [11].

5 Conclusion

It can be concluded that the degree of protection does not suit well to evaluate the effectiveness on the removal of airborne CFU of the ventilating system for any other system than LAF. While calculating the reference concentration in the standard, the assumption of an ideal mixing of the aerosol and the operating room air is made. This does not fit to the displacement concept of LAF. It was also shown the particle emission should happen at the OT, because the emission in the background leads to the assumption of a displacement of contamination at the OT. This effect did not occur even with cylindrical dummies. Maybe instead the effect of an air curtain around the protected area appears due to the LAF.

Moreover, by using the realistic arrangement, it could be shown that the $\varepsilon_{pc}$ decreased even more compared to the standard setup with particle emission at the cylindrical dummies. This low $\varepsilon_{pc}$ leads to the assumption that when using LAF, a recirculation area is formed at the OT in a realistic arrangement. This contradicts the required displacement of airborne CFU in ORs.

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