Design of Hospital Operating Room Ventilation using Computational Fluid Dynamics

Doctoral thesis
By

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Do not aim for success if you want it; just do what you love and believe in, and it will come naturally.

David Frost
The history of surgery is nearly as old as the human race. Control of wound infection has always been an essential part of any surgical procedure, and is still an important challenge in hospital operating rooms today. For patients undergoing surgery there is always a risk that they will develop some kind of postoperative complication.

It is widely accepted that airborne bacteria reaching a surgical site are mainly staphylococci released from the skin flora of the surgical staff in the operating room and that even a small fraction of those particles can initiate a severe infection at the surgical site. Wound infections not only impose a tremendous burden on healthcare resources but also pose a major threat to the patient. Hospital-acquired infection ranks amongst the leading causes of death within the surgical patient population. A broad knowledge and understanding of sources and transport mechanisms of infectious particles may provide valuable possibilities to control and minimize postoperative infections.

This thesis contributes to finding solutions, through analysis of such mechanisms for a range of ventilation designs together with investigation of other factors that can influence spread of infection in hospitals, particularly in operating rooms.

The aim of this work is to apply the techniques of computational fluid dynamics in order to provide better understanding of air distribution strategies that may contribute to infection control in operating room and ward environments of hospitals, so that levels of bacteria-carrying particles in the air can be reduced while thermal comfort and air quality are improved.
A range of airflow ventilation principles including fully mixed, laminar and hybrid strategies were studied. Airflow, particle and tracer gas simulations were performed to examine contaminant removal and air change effectiveness. A number of further influential parameters on the performance of airflow ventilation systems in operating rooms were examined and relevant measures for improvement were identified.

It was found that airflow patterns within operating room environments ranged from laminar to transitional to turbulent flows. Regardless of ventilation system used, a combination of all airflow regimes under transient conditions could exist within the operating room area. This showed that applying a general model to map airflow field and contaminant distribution may result in substantial error and should be avoided.

It was also shown that the amount of bacteria generated in an operating room could be minimized by reducing the number of personnel present. Infection-prone surgeries should be performed with as few personnel as possible. The initial source strength (amount of colony forming units that a person emits per unit time) of staff members can also be substantially reduced, by using clothing systems with high protective capacity.

Results indicated that horizontal laminar airflow could be a good alternative to the frequently used vertical system. The horizontal airflow system is less sensitive to thermal plumes, easy to install and maintain, relatively cost-efficient and does not require modification of existing lighting systems. Above all, horizontal laminar airflow ventilation does not hinder surgeons who need to bend over the surgical site to get a good view of the operative field.

The addition of a mobile ultra-clean exponential laminar airflow screen was also investigated as a complement to the main
ventilation system in the operating room. It was concluded that this system could reduce the count of airborne particles carrying microorganisms if proper work practices were maintained by the surgical staff.

A close collaboration and mutual understanding between ventilation experts and surgical staff would be a key factor in reducing infection rates. In addition, effective and frequent evaluation of bacteria levels for both new and existing ventilation systems would also be important.

**KEYWORDS**

Computational Fluid Dynamics (CFD), Ventilation System, Hospital Operating Room, Bacteria Carrying Particle, Surgical Site Infection, Colony Forming Unit, Airborne Particle Control, Air Quality, Thermal Comfort, Active-Passive Air Sampling methods
SAMMANFATTNING

Tidigt i mänsklighetens utveckling har kirurgen funnits med i bilden. Hantering av infektioner har genom tiderna varit en oundviklig del av alla kirurgiska ingrepp, och finns kvar ännu idag som en viktig utmaning i operationssalar på sjukhus. För patienter som genomgår kirurgi finns alltid en risk att de efter ingreppet utvecklar någon behandlingsrelaterad komplikation.

Allmänt accepterat är att de luftburna bakterier som når operationsområdet huvudsakligen består av stafylokokker frigjorda från hudfloran av operationspersonalen i operationssalen, och att endast en liten del av dessa partiklar behövs för att initiera en allvarlig infektion i det behandlade området. Sårinfektioner innebär inte bara en enorm börda för hälso- och sjukvårdsresurser, utan utgör också en betydande risk för patienten. På sjukhus förvärvad infektion finns bland de främsta dödsorsakerna i kirurgiska patientgrupper.. En bred kunskap och förståelse av spridningsmekanismer och källor till infektionsspridande partiklar kan ge värdefulla möjligheter att kontrollera och minimera postoperativa infektioner. Denna avhandling bidrar till lösningar genom analys av en rad olika ventilationssystem tillsammans med undersökning av andra faktorer som kan påverka infektionsspridningen på sjukhus, främst i operationssalar.

Syftet med arbetet är att med hjälp av CFD-teknik (Computational Fluid Dynamics) få bättre förståelse för olika luftspridningsmekanismers betydelse vid ventilation av operationssalar och vårdinrättningar på sjukhus, så att halten av bacteriebärande partiklar i luften kan minskas samtidigt som termisk komfort och luftkvalité förbättras.
Flera luftflödesprinciper för ventilation inklusive omblandade strömning, riktad (laminär) strömning och hybridstrategier har studerats. Simuleringar av luft-, partikel- och spårgasflöden gjordes för alla fallstudier för att undersöka partikelevakuering och luftomsättning i rummet. Flera viktiga parametrar som påverkar detta undersöktes och relevanta förbättringar föreslås i samarbete med industrin.

Av resultaten framgår att mängden genererade bakterier i en operationssal kan begränsas genom att minska antalet personer i operationsteamet. Infektionsbenägna operationer skall utföras med så lite personal som möjligt.

Den initiala källstyrkan (mängden kolonibildande enheter som en person avger per tidsenhet) från operationsteamet kan avsevärt minskas om högskyddande kläder används.

Av resultaten framgår också att ett horisontellt (laminärt) luftflöde kan vara ett bra alternativ till det ofta använda vertikala luftflödet. Ett horisontellt luftflöde är mindre känsligt för termisk påverkan från omgivningen, enkelt att installera och underhålla, relativt kostnadseffektivt och kräver vanligen ingen förändring av befintlig belysningsarmatur. Framför allt begränsar inte denna ventilationsprincip kirurgernas rörelsemönster. De kan luta kroppen över operationsområdet utan att hindra luftflödet. En flyttbar flexibel skärm för horisontell spridning av ultraren ventilationsluft i tillägg till ordinarie ventilation undersöker också. Man fann att denna typ av tilläggsventilation kan minska antalet luftburna partiklar som bär mikroorganismer om operationspersonalen följer en strikt arbetsordning.

Bra samarbete och förståelse mellan ventilationsexperter och operationsteamet på sjukhuset är nyckeln till att få ner infektionsfrekvensen. Det är också viktigt med effektiva och
frekventa utvarderingar av bakteriehalten i luften, för såväl nya som befintliga ventilationssystem.

**NYCKELORD**

Computational Fluid Dynamics (CFD), ventilationssystem, operationssal på sjukhus, bakteriebärande partikel, infektion i samband med operation, kolonibildande enhet, kontroll av luftburna partiklar, luftkvalitet, termisk komfort, aktiva-passiva provtagningsmetoder för luft
LIST OF PAPERS

The current doctoral thesis is based upon the following six scientific articles, appended in full at the end of the text:


Paper 6: Sadrizadeh, Sasan and Sture Holmberg. "Thermal comfort of the surgical staff in an operating room - a numerical study on laminar and mixing ventilation systems" In: Proceedings of 14th International Conference on Indoor Air Quality and Climate. July 3-8, 2016; Ghent, Belgium
Further related peer-reviewed journal and conference papers:

**Paper 7:**

**Paper 8:**

**Paper 9:**
Sadrizadeh, Sasan and Peter V. Nielsen. "Numerical simulation on impact of surgeon posture on particles distribution in a turbulent mixing operating theatre" *Submitted.*

**Paper 10:**
Sadrizadeh, Sasan, and Sture Holmberg. "Traffic patterns effects on surgical site infection in the operating room" In: Proceedings of 13th International Conference on Indoor Air Quality and Climate. July 7-12, 2014; Hong-Kong

**Paper 11:**

**Paper 12:**

**Paper 13:**
**Paper 14:**

**Paper 15:**

**Paper 16:**

**Paper 17:**

**Paper 18:**

**Paper 19:**

**Paper 20:**


Sadrizadeh, Sasan, and Shia-Hui Peng" Sensitivity analysis in numerical simulation of indoor airflow-Boundary conditions" In: Proceedings of 14th International Conference on Indoor Air Quality and Climate. July 3-8, 2016; Ghent, Belgium

Sadrizadeh, Sasan, and Adnan Ploskić. "On the boundary conditions of numerical particle simulation in indoor environment" In: Proceedings of 14th International Conference on Indoor Air Quality and Climate. July 3-8, 2016; Ghent, Belgium

Sadrizadeh, Sasan, and Peter V Nielsen. "Workshop on CFD prediction of non-isothermal flow – How to minimize the user factor?" In: Proceedings of 14th International Conference on Indoor Air Quality and Climate. July 3-8, 2016; Ghent, Belgium


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# NOMENCLATURE

## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>LAF</td>
<td>(ultra-clean) Laminar Air Flow</td>
</tr>
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<td>ACH</td>
<td>Air Changes per Hour</td>
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<tr>
<td>BCP</td>
<td>Bacteria Carrying Particle</td>
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<tr>
<td>CFU</td>
<td>Colony Forming Units</td>
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<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
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<tr>
<td>DNS</td>
<td>Direct Numerical Simulation</td>
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<tr>
<td>DRW</td>
<td>Discrete Random Walk</td>
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<tr>
<td>GCI</td>
<td>Grid Convergence Index</td>
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<tr>
<td>IT</td>
<td>Instrument Table</td>
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<tr>
<td>LPT</td>
<td>Lagrangian Particle Tracking</td>
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<tr>
<td>LES</td>
<td>Large Eddy Simulation</td>
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<tr>
<td>MS</td>
<td>Mayo Stands (Table)</td>
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<tr>
<td>OR</td>
<td>Operating Room</td>
</tr>
<tr>
<td>OT</td>
<td>Operating Table</td>
</tr>
<tr>
<td>PPD</td>
<td>Percentage Dissatisfied</td>
</tr>
<tr>
<td>PMV</td>
<td>Predicted Mean Vote</td>
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<tr>
<td>RNG</td>
<td>Re-Normalization Group</td>
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<tr>
<td>RSM</td>
<td>Reynolds Stress Model</td>
</tr>
<tr>
<td>RANS</td>
<td>Reynolds-averaged Navier-Stokes</td>
</tr>
<tr>
<td>SD</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td>STK</td>
<td>Stokes Number</td>
</tr>
<tr>
<td>SSI</td>
<td>Surgical Site Infection</td>
</tr>
<tr>
<td>UDF</td>
<td>User Defined Functions</td>
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</tbody>
</table>
Latin Symbols

c \quad \text{volumetric concentration of bacteria-carrying particle}

C_d \quad \text{drag coefficient of sphere-shaped particles}

d_c \quad \text{characteristic dimension of the obstacle}

d_p \quad \text{particle diameter}

f_{cl} \quad \text{clothing surface area factor in Fanger's model}

F_D \quad \text{inverse of relaxation time}

F_s \quad \text{factor of safety in GCI equation}

F_x \quad \text{additional force terms per unit mass, i.e. Brownian force}

g \quad \text{gravitational acceleration}

h_{conv} \quad \text{convective heat transfer coefficient in Fanger's model}

M \quad \text{metabolic rate in Fanger's model}

n_d \quad \text{number of data points in GCI equation}

n_p \quad \text{number of personnel}

p \quad \text{formal accuracy order of the algorithm in GCI equation}

p_w \quad \text{water vapour partial pressure, in Fanger's model}

Q \quad \text{airflow rate}

q_s \quad \text{source strength for a person}

r \quad \text{refinement factor between the coarse and fine grid in GCI equation}

Re \quad \text{Reynolds number}
\( S_\varphi \) source term in Navier-Stokes equation

\( t \) time

\( T_a \) air temperature in Fanger's model

\( T_{cl} \) clothing surface temperature in Fanger's model

\( T_r \) mean radiant temperature in Fanger's model

\( u \) fluid velocity

\( u_p \) particle velocity

\( U_\infty \) free-stream velocity

\( \vec{V} \) velocity vector in Navier-Stokes equation

\( W \) effective mechanical power in Fanger's model

\( y^+ \) dimensionless distance from the wall

**Greek Symbols**

\( \varphi \) each of three velocity components \((u,v,w)\) and mean temperature \((T)\)

\( \varepsilon_{rms} \) relative error in GCI equation

\( \mu \) molecular (dynamic) viscosity

\( \xi_1, \xi_2, \xi_3 \) constants in particle drag equation

\( \rho \) fluid density

\( \rho_p \) particle density

\( \Gamma_\varphi \) effective diffusion coefficient in Navier-Stokes equation
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INTRODUCTION

Background

The history of surgery is nearly as old as the human race. Control of wound infection has always been an essential part of any surgical procedure, along with control of pain and bleeding. From ancient times to the present, people have tried to improve surgical techniques, but wound infection is still an important challenge in hospital operating rooms (ORs) today. Patients undergoing surgery are always at risk of developing postoperative complications due to infection at the wound site.

Surgical site infections (SSIs) commonly refer to infections that are localized to the incision site after surgical activities. These infections can be either superficial involving the skin only, or they can be more serious and involve tissues, organs and implanted material. SSI is very case-dependent among patients undergoing surgery. Some patients may be at higher risk of developing postoperative SSIs due to factors such as age, underlying medical conditions, invasiveness of the surgery and duration of the procedure.

SSIs can contribute to higher rates of patient morbidity and mortality, loss of productivity, increased hospitalization time and patient dissatisfaction. These infections can also impose a substantial economic burden on both healthcare provider and the patient.

It is widely accepted among experts in the area of infections that Staphylococcus aureus is the most commonly implicated bacterial pathogen found in the OR [1,2] and is one of the important causes of skin and soft tissue infections [3]. Recently, the increasing rate of antimicrobial drug resistance has been a matter of great concern, as many types of Staph bacteria that may initiate SSI have now become resistant to many antibiotics. The danger posed by growing resistance to antibiotics has been described a global
threat, a “ticking time bomb” that should be ranked alongside terrorism on the list of threats to the human race [4].

It was reported in 2006 that SSIs occur in 7% of surgical procedures and are the third most frequently reported group of hospital-acquired infections in Sweden [5,6]. A recent report from The National Board of Health and Welfare in Sweden estimated that patients with hospital-acquired infection occupy 10% of all beds at somatic care departments. In addition, approximately 1500 patients die every year in Sweden due to such infections.

**Motivation for the research**

Normal skin flora of surgical team members or patients causes more than half of all infections in OR environments. Pathogens originating from human skin flora can disperse into OR air and further deposit on surfaces. They can also spread by direct contact between carrier and wound. Whyte et al. [7] reported that, in a total hip replacement, the number of airborne bacteria depositing directly into the wound was only 30% of the total bacteria and the rest were derived from indirect airborne routes.

General control of contaminants to minimize risk of postoperative SSIs is usually managed by using an efficient ventilation system to dilute and evacuate contaminants from the OR [8–11], by increasing the protective efficacy of staff [12,13], as well as by reducing the number of personnel and the level of their activity in the OR [14].

Various ventilation principles have been used in ORs including fully mixed, laminar airflow (LAF), displacement, hybrid and local ventilation. The actual resulting airflow patterns within the ORs and healthcare facilities still remain a subject of debate among professionals. Precise clinical investigations show that airflow fields measured in such areas range from laminar to transitional to
turbulent flows or a combination of all under transient conditions [8,15].

The airflow assessment in experimental investigations and in analytical calculations usually relies on many assumptions. Therefore, there is a need for more detailed understanding of flow physics and for comprehensive description of real airflow patterns and contaminant distribution in hospitals and healthcare facilities.

Objectives and research questions

The primary objective of this work has been to investigate the impact of ventilation airflow systems on the transmission of particles within hospital operating rooms. Main characteristics of different ventilation principles were compared on the basis of numerical simulations using computational fluid dynamics (CFD) techniques. A range of factors that can influence the bacteria carrying particle (BCP) concentration and thus increase the infection rate were considered. Trials were then made to examine how changes in the design of a ventilation system can improve thermal comfort, reduce contaminants and provide better air quality. Finally, in order to support architects and design engineers and to improve ventilation efficiency, this work has further investigated the influence of a number of further parameters on the design of ventilation systems.

To achieve the above objectives, the following research questions have been formulated and comprehensively addressed in the thesis work for cases studied.

1. What is the optimal ventilation strategy in relation to airflow pattern to give the lowest possible BCP concentration and thus a reduced rate of surgical site infections?
2. How would the number and activity of surgical staff affect the amount of airborne particles within the critical area of interest for surgery?

3. What are the numerical approaches suitable for CFD analysis, such as turbulence models and particle-tracking methods, in assessing ventilation effectiveness in operating rooms and hospital wards?

Limitations

The present work has been undertaken by means of numerical investigations only. Direct measurement was not performed, since the examined operating room was not available at the time of the study. Model validation was therefore performed through comparisons to experimental data from the literature. Therefore, lack of direct experimental measurements in a similar operating room environment is the main limitation of the study.

The CFD simulations also had some limitations for the use of commercial finite volume codes, as in the ANSYS package. This has to some extent limited the range of modelling options for selection and testing of different emerging turbulence models and numerical schemes. All the simulations in this study were performed using turbulence models in the context of Reynolds-averaged Navier-Stokes (RANS) methods, which, as generally recognized, possess inherent empirical assumptions and thus related limitations.
LITERATURE REVIEW

Bacteria Source and Size Distribution

Over recent decades, the importance of airborne bacteria in the ORs has been a matter of interest and dispute. The number of viable airborne bacteria is highly correlated to risk of infection to the surgical patient. Almost 80-90% of bacterial contamination detected in an operative wound comes from the surrounding air [16,17].

In 1980, Hambraeus et al. [18] showed that both aerobic and anaerobic skin bacteria are dispersed into the air and survive sufficiently long to make an airborne route of wound infection.

Transfer of bacteria from the patient's skin may also be likely to occur due to the surgical procedure, although this is a matter of continuing debate. Transport mechanisms of BCPs are much more important in infection-prone surgeries such as orthopaedic replacement, because bacterial species causing SSI belong to the normal skin flora. Lidwell [19] has shown that for an operation period of around 1 hour, the total number of BCPs falling into a wound was about 270/cm², with a particle settling velocity of about 0.3 m/min [20]. However, the infection risk depends on many factors including the species and virulence of the bacteria, the integrity of the patient’s host defences and the viability of settled bacteria at the time of wound closure.

The distribution of bacteria, especially S. aureus, in different sites on the human body surface was thoroughly addressed in previous research studies [2,7,21–30]. However, the size and total amount of bacteria released from each individual still remains controversial. During moderate physical activity, a person releases about 10 million particles every day. The release rate may increase to $10^4$ particles per minute during walking activities, but only a small fraction of these particles (5-10%) carry bacteria [2,31]. Several studies reported that particles ranging from 2.5μm to 20μm
may act as vehicles carrying viable bacteria and should be considered as infectious particles [32,33]. Other studies have implicated different size distributions of particles, such as 5-10μm [11,25,31,34] and 5-60μm [35–37].

In reality, the fragment release rate from people would be influenced by several factors and vary widely from time-to-time and person-to-person, and the phenomenon is not yet fully understood. Some individuals, well-known as dispersers, release markedly more bacteria, and their presence in the OR may increase the prevalence of wound infection and SSI [38,39]. Men shed more bacteria and with a higher count of S. aureus than women, and women shed more frequently in the postmenopausal phase of life [2,40–42]. In addition, a young person is more likely to release lower amounts of bacteria compared to an older one.

A large number of studies have reported that most BCPs are emitted mainly from the lower part of the body, especially the perineum and the inside of the thighs [36,43–47]. Any person with a skin disorder or a septic lesion may of course release considerably more pathogen-containing particles than a healthy individual. Minimizing bacterial concentration in the OR requires the cooperation of all personnel and they should actively promote the basic principles of antisepsis regularly. Therefore, it is highly recommended that healthcare workers with any type of unusual skin shedding, such as indicated by itching, flaking skin, dermatitis, dandruff and chronic coughing should be excluded from OR until their health problems are resolved.

The release rate does not only vary according to the individual but also varies according to time. A person releases particles at different daily and annual rates. In summer the release rate was found to be highest, while in wintertime the release rate dropped markedly [43]. Monthly airborne bacterial levels have been found to vary substantially, but no regular trend was reported [48,49].
Consequently, regular monitoring of airborne bacterial levels is recommended in order to reduce the risk of SSI.

The levels of bacteriological species also appeared to be considerably different between ORs, even with similar occupancy rates and air-conditioning systems [49]. This might have been due to the diverse types of surgeries performed in the ORs [33]. For instance, the bacterial count in the ORs where only traumatology surgery was performed were always found to be at a lower contamination level compared to those in ORs where dirty-infected wound operations took place. Thus, it is irrelevant to apply results obtained from one kind of surgery to other kinds of surgeries.

**Door Opening and Staff Movement**

The air movement in an operating room can be very complex since it depends on many factors including door opening, staff movement, room geometry and thermal sources. A transient flow occurs when an initially steady state is disturbed and turbulence develops due to a change in boundary conditions. A good example of this phenomenon would occur when a connecting door between two rooms is opened. The frequency of door opening and passage of persons through doors were among the most important factors found to be contributing to increased bacterial counts [50–59].

The air leakage through the door opening is a very complicated problem to study, as it varies with size of door as well as temperature and pressure differences across the opening [60,61]. The opening and closing of a door has a major impact on internal pressure and velocity distributions. It has been shown that contaminant passage is highly affected by the amount of pressure difference throughout the door opening period [56,62]. The door-opening speed and human passage, for both constant and variable speeds, have only a minor effect on air leakage, with the average flows to both directions behaving similarly [58].
Some of the previous studies reported no major difference in OR airborne bacterial counts between closed and swinging doors [57,63], whereas others found a correlation between OR door openings and elevated airborne bacterial counts [52,55]. Traffic flow pattern reported by previous studies [59,64,65] highlights the importance of change at an administrative level including logistics, improved knowledge and pre-operative planning. This would give the OR personnel essential tools to reduce door openings during surgery.

There are also other transient flow disturbances originated by moving objects and human activities, which could affect airborne infection. Staff movement can introduce more complexity in fluid flow and contaminant transport, as it depends on individuals, and thus haphazard behaviour. Turbulence and local eddies created by personnel movement, mainly entering and leaving the OR, has a direct impact on efficiency of the ventilation system, the airflow pattern and thus particle distribution.

Such movements produce a similar, but more complex, effect to door opening, and clinical assessment of them has proven difficult. Due to the above complexities, the path and suspension time of PCB become much more variable and difficult to determine.

**Ventilation systems**

The postoperative infection rate generally depends on several factors including the level of airborne bacteria and the quality of the air within the OR. It is widely accepted that clean surgery with a moderate to high risk of infection should be performed in an ultra-clean atmosphere. The accepted international definition of ultra-clean is air containing less than 10 Colony Forming Units (CFUs) per cubic metre (m³) air and corresponding surface contamination, in an OR with vertical LAF, of 350 CFU per square metre (m²) in an hour [66]. The appropriate ventilation system is
the primary means of achieving a safe and healthy indoor OR environment, so as to preserve air quality, dilute and remove airborne bacteria, odours and anaesthetic gases from surgical locations. The OR ventilation system should also provide comfortable working conditions and an appropriate level of thermal comfort for the personnel to facilitate their demanding work.

There are important differences concerning the ability of various airflow systems to prevent bacterial emission into the surgical area of OR fields. One of the most important factors regarding the ventilation system is air changes per hour (ACH) which is expressed as the volumetric airflow through the room divided by the volume of the room. Even with the same ACH, different ventilation systems reveal great differences in terms of particle removal efficiency [9,67]. Some studies have concluded that higher ACH rates lead to lower concentrations of airborne contamination [8]. Others have reported that ACH increments up to a certain level might increase swirls and vortexes and thus promote the recirculation of BCPs within the ORs [11].

Figure 1: Vertical (downward) LAF ventilation
The most common ventilation systems used in ORs today are downward Laminar Airflow (LAF) [8,34,68], mixing [14,69], displacement [70] hybrid technologies [9,71], and local and mobile ventilation [72–74]. These ventilation systems differ primarily in the methods used to supply and evacuate the air.

![Figure 2: Horizontal (cross-flow) LAF ventilation](image)

Typically, there are two types of LAF system, horizontal and vertical; and selection between them is highly case-dependent and still controversial. Liu et al. [75] and Sadrizadeh et al. [8,13] examined the performance of horizontal unidirectional airflow ventilation and found that this system can provide an important alternative to conventional OR ventilation.

They concluded that medical lamps and thermal plume induced by the temperature difference between people/equipment and environment had no clear impact on the airflow pattern of the surgical area. In another study, Memarzadeh and Manning [11] examined a vertical LAF in a numerical simulation study and concluded that this system represented the best option for an OR in terms of contamination control.
Mixing ventilation systems rely on dilution of airborne bacteria floating in the air. The clean and conditioned air is introduced into the OR through swirl or line diffusers with a high velocity. Since air in the entire space is fully mixed, temperature variations are small and the contaminant concentration is uniform.

Upward air-displacement ventilation is another room air distribution strategy and relies on natural buoyancy plumes. In this case, clean chilled air supplied near the floor at a low velocity falls towards the floor due to gravitation and spreads across the room until it meets heat sources in the OR. The chilled air then slowly rises up toward the ceiling as it absorbs heat from occupants and equipment and then is extracted out above the occupied zone, usually at ceiling height.

It was concluded by Memarzadeh and Manning that upward displacement ventilation system was more efficient in removing particles compared to mixing systems [11]. Conversely, it was shown by Friberg et al. [76] that this air distribution strategy resulted in higher surface and volumetric bacterial concentrations in the surgical zone.
Figure 4: Displacement ventilation

Hybrid ventilation technology is a modern development that is used to integrate different features of mixing and LAF ventilation components so as to offer a highly efficient ventilation solution.

Figure 5: Hybrid ventilation

This system maintains healthy indoor climate and comfort for both patient and staff members. In this technology, the surgical area at the OR centre is supplied by the LAF while the OR periphery is ventilated by mixing principles. The BCPs that washed off from the OR centre with unidirectional airflow structure are further diluted with fully mixed airflow field in the OR periphery and evacuated
by the exhaust openings. The usefulness of such a ventilation system is that it can provide the benefits of both fully mixed and laminar airflow ventilation systems.

Ventilation requirements are usually defined according to the type of surgery and indoor air quality standards in the ORs. There is common agreement among professionals that alternative ventilation systems should be used in the ORs since different surgeries require diversity in number and type of equipment, lights and personnel. Moreover, providing alternative air distribution systems offers various possibilities in the protection of staff members and the patient against pathogenic microorganisms.

Thermal comfort

Hospital and healthcare facilities need to provide a variety of indoor environments due to the diverse comfort and health needs of their occupants. The indoor air quality and thermal comfort in the hospital work environment affect both patient health and the well-being of healthcare team members [77–80]. Inappropriate thermal conditions are much more critical in an OR environment and may reduce work efficiency and increase the possibility of surgical errors [81]. There are six main factors that directly affect thermal comfort, which can be divided into two categories of personal and environmental factors.

Thermal comfort is defined as the state of mind that expresses satisfaction with the thermal environment [82]. It is also defined as the state in which there is no tendency to correct thermal conditions of an environment by occupant behaviour [83]. The human body, despite environmental changes, needs to preserve a constant internal temperature. In order to achieve this goal, the rate of body heat generation must be equal to the rate of heat loss from it. The thermoregulatory system of the human body tries to create a heat balance within a wide range of the environmental variables [84].
Thermal comfort evaluation within an enclosed environment is usually determined through Predicted Mean Vote (PMV) and the Predicted Percentage Dissatisfied (PPD) indices [84]. The model was developed by Fanger [85] using heat balance equations and empirical studies to define comfort. This model is among the most well-established models that are used for practical application and accepted for design and field assessment of comfort conditions. There are many studies that examine thermal comfort in hospital environments [77,79,81,86]. Although this model, known as classic comfort theory, has become the standard method of predicting thermal comfort for occupants, some previous laboratory and field studies proved that this model may not always be a good predictor of actual thermal sensation [87,88]. Discrepancies between actual and predicted thermal sensations reveal the complications in precise measurement of personal factors. Poor estimations of activity level and clothing insulation, in most practical settings, are likely to reduce the accuracy of PMV predictions.

The seven-point scale of thermal sensation limits the PMV index to a descriptive dimension, which would imply no pronounced satisfaction or dissatisfaction. A PMV score of zero indicates a neutral whole body thermal sensation, but this states nothing about whether the occupants are actually being pleased [89].

It has been reported that Fanger's model is well able to estimate the PPD-value for nurses and anaesthetists in colder regions. The value, however, is underestimated by this model near the comfort region [81]. The comfort prediction became even less accurate for surgeons, as the PPD-value was overestimated for them in cold regions and underestimated in warm regions.
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Computational Model

Case study

The geometrical configuration of the OR used in this study was designed by Skanska IT Nordic (Swedish construction company). Figure 6 shows the overall OR geometry and an example of its internal configuration.

Figure 6: An isometric view of the operating room model

The OR room was proposed for a new hospital (NKS, Nya Karolinska Sjukhuset) and it is under construction in Stockholm, Sweden. The OR measured L 8.5m × W 7.7m with a floor-to-ceiling height of 3.2m.
For different assessments and depending on the case studied, the range of factors examined here was: type of ventilation systems, airflow rate and air change rate per hour (ACH), number and internal constellation of staff members, as well as boundary conditions.

The effect of different numbers of personnel was studied in Paper 1 [14], starting with ten persons and reducing the number one by one down to four persons. Vertical and horizontal LAF ventilation systems were examined in Paper 2 [8]. In Paper 3 [90], a local ventilation system as a complement to the main OR ventilation was assessed. Three distinct staff clothing systems, resulting in different source strengths (mean value of CFU emitted from a person per second), were investigated in the 4th paper [13] and a combination of mobile laminar ventilation and clothing systems were simulated in the 5th paper [91]. Thermal comfort of the surgical staff under laminar and mixing ventilation systems was addressed in paper 6 [92].

Many other aspects, including the size distribution of airborne particles carrying microorganisms [14,90] and their launch location [93], thermal comfort of surgical staff and patient [92,94], impact of radiative heat transfer on air and temperature distribution [95], door opening [62], optimal position of exhaust outlets [96], staff posture and work practice [97,98], and cross infection in hospital wards [99,100], were also addressed in other papers mentioned in the paper list. In addition, sensitivity analyses of boundary conditions [101] as well as evaluation of various turbulence models for indoor airflow prediction [102] were considered.

**Boundary conditions**

It is well known that the quality of CFD simulation is closely associated with boundary conditions. The correct, realistic and precise implementation of boundary conditions would be an
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important part of any CFD simulation. Proper physical and numerical treatment of the boundaries may not only affect the accuracy, but also computational robustness and convergence speed. It has been discussed in the literature that, due to the sensitivity of boundary settings, different operators may obtain different results for the same case even with the same code [15,103,104]. In enclosed environments, the inlet-outlet boundaries may become much more important, compared to other boundaries, as the airflow pattern is highly affected by incoming air and exhaust grills [101].

In the present study, a frequently used boundary condition for the incoming air is “velocity-inlet” boundary. Depending on the case studied, uniform or non-uniform velocity and temperature profiles were imposed on the inlet by compiling a User-Defined Function (UDF). In addition, a turbulence intensity of 5-10% was used along with a hydraulic diameter of the inlet to specify inflow turbulence parameters. For the airflow exhaust openings, “pressure outlet” or “outflow” boundaries were assigned. No-slip boundary conditions were combined with zero heat flux to define adiabatic walls. A constant heat-flux was also assigned to the wall of all internal heat sources, including staff, patient, surgical lamps and other equipment.

For the boundary condition of particles, an “escape” boundary was assigned when the particles reached air exhaust outlets and their trajectories were terminated. The “trap” boundary was considered after they hit a rigid surface, and no rebounding was taken into account [105].

Mesh strategy and grid independency

A grid sensitivity analysis was conducted in each case study to determine the effect of grid resolution on the accuracy of the numerical solutions. In addition, the Grid Convergence Index
(GCI) as proposed by Roache (1994) was calculated in order to estimate grid uncertainty:

\[ CGI(u) = F_s \frac{\epsilon_{\text{rms}}}{r^p - 1} \]  

Eq. 1

Here, \( F_s \) is the factor of safety and recommended to be 3, \( p \) is the formal accuracy order of the algorithm, with a second-order solution of \( p = 2 \), and \( r \) is the refinement factor between the coarse and fine grids. \( \epsilon_{\text{rms}} \) is relative error and defined as:

\[ \epsilon_{\text{rms}} = \sqrt{\frac{\sum_{i=1}^{n_d} \left( \frac{u_{i,\text{coarse}} - u_{i,\text{fine}}}{u_{i,\text{fine}}} \right)^2}{n_d}}, \]  

Eq. 2

where \( u \) is velocity magnitude and \( n_d \) is the number of data points. To estimate the GCI, root-mean-square (rms) error of velocity magnitude was calculated at one hundred points uniformly distributed through the computational domain. The GCI(\( u \)) values were all less than 5-10\%, depending on different cases studied for the grid adopted, indicating that the grids were sufficiently fine.

**Governing equations for airflow calculation**

Starting from the fundamental principles for mass, momentum and energy conservation, a system of equations can be derived to describe the three-dimensional behaviour of fluid flow and heat transfer in an OR room. Due to the large scale of the room geometry and the flow complexity involved in indoor turbulent flow simulation, Direct Numerical Simulation (DNS) and Large Eddy Simulation (LES) approaches became impractical. These approaches are very demanding on computing resources and have been rarely adopted in practical applications. For design and
evaluation of air movement in enclosed environments, the mean flow is often the main focus, which can be solved using the conventional Reynolds-Averaged Navier-Stokes (RANS) approach. Due to its computational efficiency and reasonable accuracy, the RANS modelling approach remains an industrial mainstay for a wide range of turbulent flows in industrial applications. This model is usually employed to analyse turbulent flows, heat transfer, thermal comfort and contaminant dispersion.

The governing equations can be written in a general form of:

\[
\frac{\partial}{\partial t} (\rho \varphi) + \nabla \cdot (\rho \varphi \vec{V} - \Gamma_\varphi \nabla \varphi) = S_\varphi, \tag{3}
\]

where \( t \) is the time, \( \rho \) is the air density, \( \varphi \) represents a dependent variable, such as the three mean velocity components \( u, v, w \) and mean temperature, \( \vec{V} \) is the velocity vector. \( S_\varphi \) is the source term and \( \Gamma_\varphi \) is the effective diffusion coefficient for each dependent variable.

In this study, RANS models, including the Re-Normalization Group (RNG) \( k-\varepsilon \) [107] and \( \vec{V}^2 - f \) [108] turbulence models, were employed to simulate the turbulent flow field. It was shown that these selected RANS turbulence models are appropriate for the indoor airflow simulations presented in this work [102,109].

**Numerical model for particle motion**

There are two main numerical approaches for modelling particle motion, namely Eulerian particle tracking and Lagrangian particle tracking (LPT). Each algorithm has its pros and cons and selection from the two methods is based on the research field and the likely computational cost. Both methods compute the flow field based on the Eulerian framework, but particle phases are treated differently. With the Lagrangian method, the trajectory of a discrete phase
particle is calculated by integrating the force balance over the single particle. The Eulerian method, on the other hand, considers the particles as a continuum and computes the conservation equations for the particle phase to give the details of the particle concentration field. Several recent studies claimed that the LPT approach could be more accurate compared to the Eulerian method in predicting pollutant dispersion and distribution [110,111] and thus the Lagrangian method was used in the present analysis.

In the LPT method, the particle trajectory is predicted by solving the particle motion equation, which can be written as:

\[
\frac{du_p}{dt} = F_D (u-u_p) + \frac{g (\rho_p - \rho)}{\rho_p} + F_x
\]

Eq. 4

In this equation, the subscript \( p \) refers to the particle whereas the un-subscripted quantities refer to the air. \( u \) is the velocity vectors, \( \rho \) is density, \( t \) is time and \( g \) is gravitational acceleration. The term \( F_x \) is used to incorporate additional terms such as the Saffman's lift force and Brownian force.

\( F_D \) is the inverse of relaxation time and can be computed by:

\[
F_D = \frac{18 \mu C_d Re_p}{\rho_p d_p^2} \frac{C_d Re_p}{24}
\]

Eq. 5

where \( \mu \) is the molecular viscosity of the air, \( d_p \) and \( Re_p \) are the diameter and the Reynolds number of particles. \( C_d \) is the drag coefficient and defined as follows:

\[
C_d = \frac{\xi_1}{Re} + \frac{\xi_2}{Re^2} + \xi_3
\]

Eq. 6

where \( \xi_1, \xi_2 \) and \( \xi_3 \) are the constants given by Morsi and Alexander [112].
A UDF was combined with the LPT method to calculate concentration distribution from the particle pathways. In addition, the Discrete Random Walk (DRW) model was employed to incorporate the stochastic velocity fluctuations in the fluid phase.

To characterize the behaviour of particles suspended in the airflow field, the Stokes number ($STK$) was also considered in this study. For each case study, the highest possible value of $St$ was calculated. It was shown in previous studies that particles with STK of 0.1 and below behave like fluid particles and appear to follow the recirculating eddies, whereas those with $STK \approx 1$ are less able to respond to the small-scale flow pattern, and the dynamic of such particles is weakly affected by turbulent dispersion[113,114]. The $STK$ is defined as:

$$STK = \frac{\rho_p d_p^2 U_\infty}{18 \mu d_c}$$  \hspace{1cm} Eq. 7

where $\rho_p$ and $d_p$ are particle density and diameter, respectively $U_\infty$ is the free-stream air velocity, $\mu$ is the air molecular dynamic viscosity and $d_c$ is the characteristic dimension of the obstacle. The highest possible value of Stokes number, in all case studies based on the largest particle size and velocity, was calculated as being in the order of $10^{-3}$. This value of Stokes number clearly shows that the particles are most likely to follow the airflow motions and a small variation in particle size and velocity has little impact on particle trajectories.

The stochastic track of particles in the LPT method may impose substantial uncertainties into the concentration calculation. The particle trajectory calculation was repeated several times in order to overcome such uncertainties and to achieve statistically reliable results. It has been shown by Zhang and Chen [110] that the solution becomes stable when an adequate number of particles are simulated.
In all case studies, the interaction between particle and airflow field was considered as one-way coupling, as has also been recommended by others [110,113,115]. Additional forces such as Basset history, pressure gradient and virtual mass and Brownian diffusivity were disregarded for the size particles considered in this study. However, the Saffman lift force was incorporated [116,117].

**Thermal Comfort**

Assessment of thermal comfort was performed by applying Fanger's model [85]. Here, a UDF was used to calculate the relative humidity and further applied to the CFD simulation results for the PMV and PPD values. The PMV and PPD values can be calculated as follows:

\[
PMV = \left[ 0.303 \exp(-0.036M) + 0.028 \right] \\
\times \left\{ (M - W) - 3.69 \times 10^{-8} f_d \left[ (T_d + 273.15)^4 - (T_r + 273.15)^4 \right] \right\} \\
- f_d h_{conv} (T_d - T_w) - 3.05 \left[ 5.733 - 0.007 (M - W) - 0.001 p_u \right] \\
- 0.42 \left[ (M - W) - 58.15 \right] - 0.0173 (5.867 - 0.001 p_u) \\
- 0.0014 M (34 - T_w)
\]

**Eq. 8**

\[
PPD = 100 - 0.95 \cdot \exp\left( -0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2 \right)
\]

**Eq. 9**

The acceptable thermal environment for general comfort is recommended as -0.5 < PMV < 0.5. A more detailed explanation of the above equation is given in ISO 7730-2005 [84].
Microbiological Air-sampling Methods

Experiment

Frequent air sampling allows a satisfactory assessment of particle distribution within healthcare settings. Various types of air sampling should be adopted in order to ensure that a ventilation system meets standard requirements.

In experimental measurements, there are two different approaches frequently employed to monitor the microbiological population in the air, i.e. passive monitoring and active sampling.

Normally, active sampling is adopted to map the volumetric particle concentration, and passive monitoring is used to measure the sedimentation rate of viable particles on surfaces.

The plates are then incubated to allow visible colonies to develop and be counted. Sedimentation plates are restricted in their applications since they are only able to monitor BCPs that precipitate out of the air and settle down on a surface during the exposure time [6]. Therefore, this method should be used only in cases where the particles are allowed to settle undisturbed, which does not occur with high airflows. Moreover, the plates cannot sample specific volumes of air, so results are not quantitative.

An analytical equation, as given in Eq. 10, can be used to estimate particle concentration in an enclosed environment. However, this equation relies on two assumptions. First, that the OR is in stationary condition and, second, that the airborne particles are uniformly distributed throughout the OR [6].

\[ c = \frac{n_p \times q_s}{Q} \]  

Eq. 10

Here, \( c \) is the volumetric concentration of BCPs (CFU/m\(^3\)), \( n_p \) is the number of personnel, \( q_s \) is source strength (CFU/s emitted from a person) and \( Q \) is airflow rate (m\(^3\)/s).
CFD simulation

Microbiological air sampling should be performed periodically during surgical activities to provide information regarding bacteria levels in the surgical zone. Performing microbiological air sampling during a given surgical procedure may involve several ethical and logistical considerations, and frequently cannot be repeated.

CFD simulations of BCP distribution in the hospital indoor environment could be a potential alternative to direct measurement. Therefore, in the current study, air-sampling methods were numerically simulated to map the BCP distribution within the OR. More comprehensive details about the numerical approach of active and passive samplings have been given in Papers 1, 2 and 3 [8,14,90].

Recovery Test

Recovery tests are usually performed to examine the performance of air ventilation systems in removing airborne particles within a certain time limit [118]. Cleanliness recovery performance after being exposed to a particle generation event is among the most important performance characteristics of ventilation system. The recovery time is the time taken for particle concentration to decline by two orders of magnitude (e.g. from 1000 to 10).

In this study, based on DIN 1946-4 [119], the OR room was exposed to 3500 particles (0.5μm) per cubic metre of air.
Model Validation

For the purpose of validation, three different cases were chosen as described below.

Validation study 1

A well-documented experimental benchmark test, which was carried out at the Aalborg University, was used as a reference to validate CFD predictions of the airflow field (Figure 7-a). The experimental setup was a sitting-posture manikin in a wind tunnel with box-shaped geometry (L × H × W = 2.44m × 2.46m × 1.2m). The manikin was positioned at the box centre-line in a distance of 0.7m from the inlet (Figure 7-b).

The incoming air was supplied uniformly over the full cross-sectional area of the wind tunnel, in front of the thermal manikin, and it was evacuated through two circular exhaust openings behind the manikin. The air was introduced from a surrounding laboratory hall to the wind tunnel at 0.27±0.02 m/s and with a mean temperature of 20.4 ± 0.1 °C. The manikin surface temperature was set at 34 °C without clothing, so as to achieve fast
and accurate heat loss levels. Air velocities and temperature were measured at different locations, both in front of and behind the manikin, as shown in Figure 7-c.

Figure 8: Velocity profiles at L1 and L3 predicted with nine different turbulence models.

Figure 8 shows the velocity profile predicted with different turbulence models at the two vertical lines L1 & L3.

Figure 9: Temperature profiles at L1, L2 and L3 predicted with nine different turbulence models.
The difference between predicted velocity profile and measurement data at L1 is less than 1%, but there is a large discrepancy between the predicted and measured airflow velocity at L3.

Of all turbulence models, RNG $k$-$\varepsilon$ and $\overline{v'^2} - f$ models showed the most closely corresponding results.

Figure 9 shows the predicted temperature profile with nine turbulence models at three different vertical lines L1, L2 & L3. As for velocity profile, temperature prediction is highly accurate in front of the seated manikin (L1 and L2) but a discrepancy can be observed at the rear side of the wind tunnel, close to the exhaust outlets. In both cases, velocity and temperature were under-predicted at the line L3, especially at floor level. A detailed explanation regarding such discrepancies were given by Sadrizadeh and Peng [101].

Among all turbulence models used here, Realizable $k$-$\varepsilon$ was the most robust and easy to converged turbulence model and RSM model were slightly more accurate in some ways.

Figure 10: Velocity vectors on the mid plane of the wind tunnel box, colour of manikin shows the value of $y^*$
Figure 10 shows the velocity vector field at the mid-plane of the wind tunnel-box passing through the manikin. The unidirectional airflow field from the inlet became exceedingly turbulent when passing the manikin. The intensive turbulence fluctuations and recirculation (eddy) in the rear side of the manikin presented a major challenge to the turbulence models.

Surface colour of the manikin represents the dimensionless wall distance ($y^+$) value (of the first near-wall grid point), which falls within the acceptable value for indoor airflow simulations.

Validation study 2

From the conclusion of the previous section and in view of the appropriateness of the RNG $k$-$\varepsilon$ turbulence model for indoor airflow simulations, this model was further applied to the current validation case.

Figure 11: The geometry and measured point of velocity and particle concentration

The experimental case by Chen et al. [115] was selected where overall dimensions of the room were $L \times W \times H = 0.8\text{m} \times 0.4\text{m} \times 0.4\text{m}$. The inlet and outlet, $0.04\text{m} \times 0.04\text{m}$, are symmetrical in relation to the centre plane (Figure 11). The particle size of $10\mu\text{m}$
was chosen and concentration was normalized relative to inlet concentration. Inlet velocity was set to 0.225m/s.

![Figure 12](image)

Figure 12: Comparison of measured and predicted velocity and particle concentrations at three different locations

Figure 12 shows comparison of simulated velocity and particle concentration to experimental data. Both velocity profile and the Lagrangian DRW simulation agree well with measurements and the model validation is therefore considered successful.

**Validation study 3**

An additional case validation was carried out using full-scale field airflow and particle concentration measurements by Zhao et al. [120]. Measurements were performed in an ISO Class-5, single-bed protective environment equipped with a down-flow ventilation system design.

The configuration of the ward room and its adjacent bathroom with overall dimension L 3.3m × W 3.1m × H 2.5m is shown in Figure 13-a. The particle source location together with measured location of the velocity and particle concentration is shown in Figure 13-b. The incoming air was introduced into the patient care and bathroom areas through a ceiling opening and evacuated through exhaust openings on the vertical walls. The air supply
velocity was 0.28m/s and 0.36m/s in the patient care area and bathroom respectively.

Figure 13: (a) Layout of the validation case and (b) floor plan of the test points

Part of the supplied air to the clean ward entered the bathroom through a door gap. Fine particles with an aerodynamic size of 0.5-1μm and density of 914 kg/m³ were continuously released over the toilet seat. A detailed explanation of the experiment setup has been given by Zhao et al. [120].

Figure 14: Comparison of measurement and simulated velocity at L1, L2, and L3
The simulated and measured velocities and the dimensionless particle concentration at test locations are shown in Figures 14 and 15, respectively. A comparison of results indicated that the simulated velocity correlated strongly with experimental data and provided a reasonable prediction of the particle concentration distribution.

The simulation for P1, P2, and particularly P4 gave a considerably lower particle concentration prediction than measurements, especially in the lower parts of the bathroom. This may have been due to particle leakage from the connection between the generator and pipe during experiments, which was close to P4, as explained by Zhao et al. [120].

Figure 15: Comparison of simulated and measured dimensionless particle concentration with dimensionless concentration defined as the local concentration of P5 at the height of 0.8 m

The leakage influence for P1 and P2 was much smaller than for P4, as they were located farther away from the source. Overall, the simulated prediction of the airflow field and particle distribution was satisfactory and the mathematical model was validated.
RESULTS AND DISCUSSION

Number and position of surgical staff

Effect of staff numbers and their internal constellation were addressed in the first paper [14]. From the results, it can be concluded that increasing staff numbers within the surgical areas can cause a dramatic rise in particle deposition and distribution.

![Figure 16: The simulated BCP concentrations as a function of staff number at different particle diameters (active air sampling method) [14]](image)

The growth rate may not have been linear due to influential factors such as different distances of the staff as sources to the sampling areas, local airflow patterns and source strength. In infection-prone surgeries, (i.e. orthopaedic and transplant surgeries) movement and number of personnel should be as limited as possible. Work practice of surgical team members was also important and it was recommended that more care be given to their posture.

Different ventilation systems

The performance of vertical and horizontal LAF ventilation systems on particle deposition and distribution in the OR environment were addressed in the second paper [8]. It has been
concluded that horizontal LAF may be the best ventilation system and a good alternative to vertical LAF, as this ventilation system is easy to install, affordable and does not require modification of existing lighting systems.

![Temperature contour plots](image)

**Figure 17:** Temperature contour plot at the operating table (50 ACH); (a & b) Horizontal and (c) Vertical. [8]

It was shown that horizontal LAF is less sensitive to thermal plumes and obstacles such as lamps and medical equipment. Further restrictions and limitations should also be considered for this system in use, such as modifying staff work practices.

A comparison between particle concentrations, estimated using Eq. 10, and CFD simulation results was shown in Figure 18.
RESULT AND DISCUSSION

Figure 18: Volumetric BCPs (cfu/m³) counts during simulated surgery with horizontal and vertical ventilation strategy; fully mixed (analytical solution) shows as a reference [8].

It was clearly shown that using this equation to calculate the BCP concentration may result in substantial errors and so this is not recommended. However, as it might give a good preliminary estimate of the average concentration in the room it may be worth using prior to further precise assessment.

Local portable laminar airflow ventilation

The influence of a mobile ultra-clean exponential laminar airflow screen on concentration, deposition and distribution of BCPs in the ORs was addressed in papers 3 and 5 [90,91].

Figure 19: BCP sedimentation rate vs. centreline velocity of the of the portable laminar airflow unit (passive air-sampling method) [90]
It was concluded that the additional mobile ultra-clean LAF screen reduced counts of airborne particles and sediment-forming BCPs. The simulation results confirmed the efficacy of such ventilation units, although the effectiveness of these ventilation systems was found to be highly affected by improper working practices of staff members, as was extensively discussed in paper 9 [97].

Figure 20: Volumetric BCP concentration at the mid-plane of the OR table with (a) Mobile airflow unit set to “off”, (b) Mobile airflow unit set to “on”.[91]

Clothing systems

The initial source strength of staff members due to different clothing systems was investigated in Papers 4 and 5 [13,91].
RESULT AND DISCUSSION

It was concluded that using clothing systems with higher protective capacity, resulting in lower source strength, might reduce the particle concentration within the OR room.

Table 1: Volumetric BCP concentration for three different source strength values in the horizontal and vertical LAF systems [13]

<table>
<thead>
<tr>
<th>Source strength</th>
<th>LAF type</th>
<th>OT CFU/m³, mean ± SD</th>
<th>MS CFU/m³, mean ± SD</th>
<th>IT 1 CFU/m³, mean ± SD</th>
<th>IT 2 CFU/m³, mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>5CFU/s</td>
<td>Horizontal</td>
<td>15.15 ± 3.21</td>
<td>15.35 ± 3.11</td>
<td>9.19 ± 2.53</td>
<td>11.48 ± 3.22</td>
</tr>
<tr>
<td></td>
<td>Vertical</td>
<td>33.93 ± 4.57</td>
<td>27.01 ± 3.57</td>
<td>11.28 ± 2.77</td>
<td>17.67 ± 3.51</td>
</tr>
<tr>
<td>4CFU/s</td>
<td>Horizontal</td>
<td>11.32 ± 3.34</td>
<td>11.41 ± 3.21</td>
<td>7.12 ± 2.41</td>
<td>8.63 ± 2.58</td>
</tr>
<tr>
<td></td>
<td>Vertical</td>
<td>29.30 ± 5.05</td>
<td>21.52 ± 3.83</td>
<td>8.32 ± 2.87</td>
<td>15.66 ± 3.08</td>
</tr>
<tr>
<td>1.5CFU/s</td>
<td>Horizontal</td>
<td>4.51 ± 4.74</td>
<td>4.13 ± 3.18</td>
<td>2.48 ± 2.83</td>
<td>3.15 ± 3.01</td>
</tr>
<tr>
<td></td>
<td>Vertical</td>
<td>10.21 ± 9.25</td>
<td>9.53 ± 8.78</td>
<td>4.02 ± 4.59</td>
<td>6.87 ± 5.86</td>
</tr>
</tbody>
</table>

LAF: Laminar airflow, OT: Operating table, MS: Mayo stands table, IT: Instrument table, CFU: Colony-forming unit, SD: Standard deviation

Inappropriate clothing is critical in OR environments and may reduce work efficiency and increase possibility of surgical errors [92,94]. A surgeon who is comfortably dressed is less likely to make an error of judgment compared to one who is perspiring in a heavy, airless gown. There is a need for more assessment of the comfort and protective efficacy of various clothing systems intended for use as operating garments.

Particle size and release position

Size distribution of BCPs was considered in the 1st and 2nd papers [14,90] (see Figures 16 and 19). It was shown that BCP deposition rate was directly correlated with particle size. This means the larger the particle sizes, the higher the possibility to settle out from the air. Additionally, particle transportation to critical zones was found to be correlated with the distance of staff as a source to the surgical zone. This means that entrance of
surgical staff into the clean zone should be limited as much as possible.

The release of particles from different human skin sites, that is, feet, head and neck, have been studied in paper 17 [93]. It was shown that particle trajectories were influenced considerably by airflow structure and turbulence in the flow field. However, particle launch position had a small effect on BCP concentration and deposition. As long as particles have not yet settled, it remains possible that they can reach the wound site or any other place in the room.

**Thermal comfort**

Thermal comfort within an OR environment supplied by mixing and LAF ventilation systems, was addressed in paper 6 [92].

![Figure 21: PMV, PPD and draught rate for the mixing ventilation systems [92]](image)

It was concluded that slightly more thermally satisfactory results could be achieved when the OR was supplied by a mixing
ventilation system. The highest dissatisfaction as shown in Figure 21 mostly related to head and neck area of surgical team members (PMV≈2). This implied that surgical staff might have felt slightly warm; and therefore a PPD value has been predicted in the range of 70–80%.
CONCLUSION

Acquiring a deep-seated infection can be a life-changing event for patients and can affect every part of their lives. Any failure in ventilation systems during surgical activity may result in development of an SSI.

Operating room ventilation systems were identified as a key factor to control the dispersion of airborne pathogenic particles. The performance of different ventilation systems is highly sensitive to the case-dependent internal constellation of obstacles and thus the design of them is highly complex. Many technical complications need to be addressed and a number of human factors need to be taken into account in order to achieve the desired outcome.

Achieving a successful outcome remains a challenge, as many technical complications have to be overcome and several variable human factors need to be incorporated into the solution.

The control of airborne particles in ORs requires comprehensive knowledge about the source and transport mechanism of the bacteria-carrying particles. The role of airflow streams as a vehicle for airborne particles should be well-understood. Nosocomial infections should become better understood by healthcare personnel in order to develop more effective prevention programmes. It is essential for surgical staff members to have basic knowledge of the principles of ventilation systems. The number of personnel is recommended to be minimized and those present in the operating room need to know that all activities should be carried out “downstream” relative to the instruments and wound area. No work should be performed between the airflow diffusers and the areas important for surgical asepsis. A new ventilation principle such as the hybrid system needs to be further assessed before being used in critical enclosed environments such as operating rooms.
Continuous maintenance and risk assessments of OR ventilation systems are crucial in operating rooms, because a minor failure in such critical systems can not only result in a detrimental effect on air quality but also jeopardize the safety of a patient undergoing surgery. Staff work practice procedures may highly influence infection control outcomes. Technical ventilation solutions alone do not guarantee clean air. Mutual understanding among ventilation experts and surgical staff together with effective and frequent evaluation of operating rooms in use, are the key to making for an easier and more straightforward further development in ventilation principles.
FUTURE WORK

While the present study has provided a detailed exploration of hospital ventilation systems, there are several aspects that remain to be investigated. The theoretical perspective outlined here calls for further research and basic development. Future research should be directed towards the further incorporation of influential factors on dispersion, distribution and transport mechanisms of bacteria-carrying particles. There is yet too little known about the most efficient and relevant numerical approach to predict airflow field and contaminant dispersion in operating room environments.

In most of the case studies, a steady-state situation was adopted. Future investigations should therefore include time dependent simulations to include the effect of human activity during an ongoing surgery. Moreover, some experimental assessment that is complementary to numerical simulation is needed, to further examine other factors that may affect ventilation performance.

Another topic for future studies is to examine the newer designs for ventilation systems based on hybrid principles, as the usefulness of such systems can be enhanced because they provide the benefit of both fully-mixed and laminar airflow ventilation systems.

While this study mostly used the Euler–Lagrange method to track the particles, the Euler-Euler method can be another option for further assessment of particle distribution.

Future studies may also include thermal comfort of staff members as well as patient hypothermia, as these factors have an essential impact on work performance of staff and well-being of patients.

Further and precise understanding of the airflow structure and particle movement should also fall within the scope of future works that could include time-dependent numerical simulations and more advanced turbulence models such as Large Eddy Simulations (LES).
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