Investigation of Airflow Distribution and Contamination Control with Different Schemes in an Operating Room

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Abstract: Controlling contamination via proper airflow distribution in an operating room becomes vital to ensure the reliable surgery process. The heating, ventilation, and air conditioning (HVAC) systems significantly influence the operating room environment, including temperature, relative humidity, pressurization, particle counts, filtration, and ventilation rate. A full-scale operating room has been investigated extensively through field measurements and numerical analyses. Computational fluid dynamics (CFD) simulation was conducted and verified with the field measurement data. The simulation was analyzed with three different operating room schemes, including at-rest conditions (case 1), normal operational conditions with personnel (case 2), and actual conditions with personnel inside and some medical equipment blocking the return air (case 3). The concentration decay method was used to evaluate this study. The results revealed that the contamination concentration in case 1 could be diluted quickly with the average value of 404 ppm, whereas the concentration in case 2 slightly increased while performing a surgery with the average value of 420 ppm. The return air grilles in case 3, blocked by obstacles from some medical equipment, resulted in the average concentration value of 474 ppm. Other than that, the contaminant dilution could be obstructed dramatically, which revealed that proper and smooth airflow distribution is essential for contamination control. The ventilation efficiency of case 2 and case 3 dropped around 6% and 17.91% compared to case 1 in the unoccupied and ideal condition. Ventilation efficiency also decreased along with decreasing the air change rate per hour (ACH), while with increasing ACH, the ventilation efficiency in case 3 actually increased, approaching case 2 in the ideal condition.

Keywords: operating room; airflow distribution; contamination control; field measurement; computational fluid dynamics

1. Introduction

The critical area of any hospital is the operating room. Anything in the operating room can endanger a patient’s life, such as a variety of bacteria and viruses [1]. Those contaminants can be transmitted through the air that can contaminate medical tools. This could be dangerous to a patient when the operating room staff members perform the procedure in the operating room [2]. HVAC systems provide comfort and sufficient quality air for patients and staff in the operating room. A comfortable and healthy environment is generally determined by temperature, humidity, and air velocity [3]. Therefore, in maintaining a clean and healthy environment for patients and healthcare workers, thermal comfort and indoor air quality requires a valid regulation. American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) standard 170 [4] mentions
directive notices in an operating room, including the number of air changes per hour, airflow distribution, room pressurization, and filtration. ASHRAE standard 62 [5] asserts that indoor pollutants can influence occupants' activities; carbon dioxide is an example of an indoor pollutant. The total carbon dioxide exposure in the room must be less than 1000 ppm: this will give health workers a comfortable and healthy condition to stay focused on the procedure. Shortness of breath, headaches, confusion, and other symptoms can occur in the room because of the high exposure to carbon dioxide.

Additionally, researchers have conducted many studies on changing the velocity of supply air to control contamination spread in the operating room. The relatively low speed in the operating room will affect the concentration of microbial carrier particles (MCP) and the room’s deposition rate. This suggests that there may be a risk of microbiological contamination from exposed surfaces to areas of low velocities, such as under lights during surgical procedures [6]. Uniform vertical laminar airflow is established, and high cleanliness is achieved in the center of the room when the surgical lamp is arranged in two axes [7]. In addition, the movement of the particles in the operating room can be affected by the position of the surgical lightings, and it was also shown that higher supply velocity (≥0.38 m/s) might affect the flow disturbance [8]. Current evidence has shown a positive relationship between the airborne concentration of bacteria-carrying particles (BCPs) in the operating room and the rate of infections. The accumulation of airborne BCPs under operating lighting poses a high risk of infection for patient safety [9]. In another study, four different supply air velocities (0.16, 0.24, 0.29, and 0.33 m/s), were investigated by Liu et al. [10]. A higher cleanliness level in the operating room can be ensured by supplying air velocities larger than 0.24 m/s. Meanwhile, when the supply air velocity increases to larger than 0.33 m/s, this will also increase bioaerosol deposition.

The air supply velocity must be optimally designed to match the energy consumption for energy saving. The HVAC system in the operating room is operated for 24 h throughout the year with intensive energy consumption [11]. The HVAC system in the operating room is operated under full load even when the room is unoccupied. Research has studied the operating room ventilation systems’ best practice for energy efficiency, health, and safety [12]. Proper design, operation, and controls can reduce these costs by as much as 65% while ensuring a healthy and safe environment for the surgical team and the patient. Concerning energy saving, a preliminary study of numerical analysis has been carried out to evaluate the air velocity distribution and concentration contours while carrying out a ACH approach in an unoccupied operating room [13].

A variety of ventilation schemes have been developed for operating room use. Each has pros and cons and may be better suited than another for operations under certain conditions. The proper functioning of OR ventilation is also affected by external and internal disruptions. By applying CFD, the present study investigates the airflow and contaminant distribution in operating rooms under different conditions [14]. CFD simulation uses field measurements that are carried out as the pedestal parameters as boundary conditions [15]. In this study, CFD simulations were performed to discover the potential of HVAC systems to control air contamination, a comfortable environment for occupants, and the possibilities of energy-efficient approaches in the operating room. This simulation is based and verified on field data collection. Other than that, CFD simulation methods were also conducted in other research fields to predict and evaluate some systems in low cost and efficient ways. Zhiyi et al. [16] investigated ventilation performance in typical apartment buildings predicted by CFD in a multi-zone airflow model. The improvement in indoor air quality (IAQ) was also conducted by the measurement and CFD simulations that are shown as valid tools for IAQ indication [17]. In addition, CFD modeling of contaminant migration in a household gas furnace was investigated by Szczepanik-Scislo [18]. The results revealed that the location of the furnace could influence contaminant accumulation and migration. Such simulations can be an essential tool when designing a ventilation system concerning a furnace to improve the removal of dangerous substances.
With the intention of achieving a good environmental condition, the concentration decay method can be used to assess indoor ventilation efficiency. Tracer gas or particle experiments could be used in CFD methods. However, the pathogens as particles could be simplified without considering their biological characteristics, as most researchers have investigated [19]. Specific piecewise-linear techniques were applied to the concentration decay method to determine the ACH values for smaller time intervals. This is necessary because the plotted semi-logarithmic decay curve itself is not linear as the ventilation rate changes with time due to the changing buoyancy force [20]. Chung [21] used carbon dioxide (CO₂) as a pollutant to evaluate the efficiency of indoor ventilation. The tracer gas was injected into the room and mixed into the air; a decrease in tracer gas concentration was logged over a given period [22]. This study investigates the contamination control in different schemes to discover performance improvements carried out through comprehensive field measurement tests as well as numerical simulation analysis.

2. System Description

The operating room is generally categorized as a positively pressurized bio-cleanroom that ensures a critical environment for infection control concerns to comply with applicable standards and regulations. The dimension of the investigated operating room was at a length of 6.3 m, a width of 6.0 m, a height of 3.0 m, and a total area of 37.8 m². The function of this operating room was heart surgery. High-efficiency particulate air (HEPA) filtered the supply air with a total of 15 units located in the center of the ceiling. The operating room was classified into ISO 7 [23] with a maximum of particles per cubic meter at a size of 0.5 μm is 352,000 or equal to the Federal Standard 209E [24] with a cleanliness level of 10,000 particles per cubic feet. The design specification of indoor environmental parameters in the investigated operating room included temperature of 22 ± 2 °C, relative humidity at 30–60%, and pressurization at 5 Pa. Figure 1 displays the HVAC system in the operating room, (a) filter in air handling unit (AHU) system to filter dirty air coming from the mixing air cabin, (b) cooling coil to cool down the temperature of the air with chilled water on the coil that comes from the process of cooling the water by the chiller, (c) heating coil for the process of heating and humidifying the air to fit with the design of the operating room, (d) fan to supply the air into the room, (e) HEPA filter to filter the air particles with the efficiency of HEPA filters over 99.97% (above 0.5 μm) so that the air entering the room becomes clean, (f) return air; the air coming from the room draughts to the AHU system and supplies the operating room.

![Figure 1](image_url). The investigated operating room: (a) HVAC system; (b) snapshot.
3. Methodology

The proposed methodology of this research is illustrated in Figure 2. It generally consists of three steps: field measurement test, CFD simulation, and performance improvement strategy.

![Figure 2. The proposed methodology framework.](image)

### 3.1. Field Measurement Tests

This operating room requires a clean environment to prevent contamination in the room because the surgical process is sensitive to environmental parameters, including temperature, relative humidity, particles, and pressurization. The field measurement tests were conducted to examine the indoor environment parameters during an unoccupied period (at-rest). Parameters taken were airflow rate, pressurization, particle counts, temperature, and relative humidity. The apparatus tests for field measurement were as follows (1) Airflow rate: a TSI model PH-731 was employed to measure the airflow rate of each HEPA in cubic meter per hour. (2) Particle counter was used to count particles in the air of an operating room. Finding out the number of particles in the room was carried out using Met One 3413, and it was measured at the height of 1.2 m above the floor within a one minute recording. (3) Temperature and relative humidity in the room are very influential on objects in a room. TSI model 9565P was used to find out the temperature and humidity value in this operating room, and it was measured at the height of 1.2 m above the floor with three times measurement. The detailed specification of the apparatus field measurement tests is shown in Table 1. Furthermore, the measurement data were validated with the results of numerical simulation. The results of this measurement data were used as the basic parameters for ensuring that the operating room is in accordance with the desired design.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Apparatus Model</th>
<th>Operative Range</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity, Pressure</td>
<td>TSI PH-731</td>
<td>0.125–12.5 (m/s)</td>
<td>3%</td>
</tr>
<tr>
<td>Particles</td>
<td>Met One 3413</td>
<td>Differential ± 3735 pa</td>
<td>2%</td>
</tr>
<tr>
<td>Temperature, Humidity</td>
<td>TSI 9565P</td>
<td>−10–60 (°C), 0–100 (%RH)</td>
<td>0.3 °C, 3%RH</td>
</tr>
</tbody>
</table>

### 3.2. CFD Simulation and Improvement Strategy

CFD was conducted to investigate the airflow distribution and concentration of airborne particles. The operating room simulation was performed using the ANSYS Fluent software version 2020 R2 [25]. Three different operating room schemes were conducted in this study to determine the performance of the HVAC system and reduce the concentration of the contaminant. The geometry was created based on the actual size and situation in the operating room, as shown in Figure 3. The study aims to prevent bacteria or even
fungi from entering the patient’s body who is undergoing the surgical process. In addition, the analyses of environmental conditions are also considered. Various cases based on the different conditions are described below.

- Case 1: at-rest condition with no personnel and equipment inside the operating room.
- Case 2: operational condition with personnel inside performing a surgery.
- Case 3: actual condition with personnel inside and equipment blocking the return air.

3.3. Airflow Modelling and Boundary Conditions

ANSYS Fluent provides several equations to solve the problems, including laminar and turbulent fluid flow problems, incompressible and compressible fluid, and other problems. In order to solve the flow and temperature fields of the problem, the equation for mass conservation, momentum, and energy is written as follows

\[
\frac{\partial \rho}{\partial t} + \nabla \left( \rho \mathbf{v} \right) = S_m
\]  

(1)

\[
\nabla = \frac{\partial}{\partial x} \mathbf{l} + \frac{\partial}{\partial y} \mathbf{j} + \frac{\partial}{\partial z} \mathbf{k}
\]

(2)
Equation (1) is the general form of mass conservation equation for incompressible and compressible flows. Where the $t$, $\rho$, $\vec{v}$, $\nabla$ are time, density, velocity, gradient operator, respectively, and $S_m$ is the mass added to the continuous phase from the dispersed second phase and any user-defined sources. ANSYS Fluent defined $\nabla$ according to the cartesian coordinate in Equation (2).

Airflow turbulence simulation uses two simulation methods carried out in this study, transient and steady-state condition with the renormalization group (RNG) $k$-$\varepsilon$ as the turbulence model. Transient conditions can be used to monitor the reduction in the concentration in the operating room with a simulation time of about 500 s with a time step of 50 s. The steady-state condition is used to validate the field measurement data for temperature and velocity. The iterative coupling calculation for this stage is solved by the SIMPLE (Semi-Implicit Method for Pressure Linked Equation) method. The numerical simulation was calculated until it reached the residual below $10^{-3}$ for the velocity and continuity, while energy residuals reached below $10^{-6}$ to produce more precise results. The general form of the RNG $k$-$\varepsilon$ model governing equation is as follows

$$\frac{\partial (\rho \phi)}{\partial t} + \nabla \left( \rho \phi \vec{V} \right) = \nabla \left( \Gamma_\phi \nabla \phi \right) + S_\phi$$

(3)

where $\rho$ is the density of air, $\vec{V}$ is the air velocity vector, $\phi$ represents each of the three components, $\Gamma_\phi$ is the effective diffusion coefficient of $\phi$, and $S_\phi$ is the source term.

Lagrangian particle tracking was used for the simulation method of particle tracking. The bioaerosol was injected into the space with the discrete phase model and simulated transiently. The particle size was 1–5 µm with a median size of 2.5 µm with a density of 1000 kg/m$^3$, which is approximately equal to the density of water. It was simulated as spherical particles. The discrete phase for supply air and outlet air was set up with “escape” boundary conditions, while the remaining surfaces such as walls, medical equipment, etc., were set up with “trap” boundary conditions. Saffman lift force and thermophoretic force for the particle phase were used in this study. The equation is as follows.

$$\frac{du_{pi}}{dt} = \frac{18 \mu}{\rho_p d_p^2} C_D Re \left( U_i - U_{pi} \right) + g_i \left( 1 - \frac{\rho}{\rho_p} \right) + F_{ai}$$

(4)

where $U_i$ and $U_{pi}$ are the velocities of the fluid and particles, respectively; $\mu$ is the molecular viscosity of the fluid; $\rho$ and $\rho_p$ are the densities of the fluid and particles, respectively; $d_p$ is the diameter of the particles; $Re$ is the particle Reynolds number; $C_D$ is the drag coefficient; $g_i$ is the gravitational acceleration in the $i$ direction; $F_{ai}$ is the additional force exerted on the particles.

A tracer gas method was carried out in this study, with simplified pathogen or particles without considering biological characteristics. Carbon dioxide (CO$_2$) was selected as a pollutant to assess indoor ventilation efficiency and environmental conditions in the operating room with different models and conditions. The boundary conditions of numerical simulation are shown in Table 2. The CO$_2$ concentration in the outdoor atmosphere is about 400 ppm, which will be used as the concentration value for supplying air from HEPA [26]. The recommended indoor CO$_2$ concentrations should be maintained at or below 1000 ppm [27]. The exhaled air from patient and personnel are set with a concentration of around 38,000 ppm [28]. Heat flux generated from each patient and surgeon are at 17.45 W/m$^2$ and 33.55 W/m$^2$, respectively [29]. The walls and door were assumed to be adiabatic, which have no heat transfer.
Table 2. The boundary condition for numerical simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Air</td>
<td>Velocity Inlet</td>
<td>Velocity: 0.298 m/s</td>
</tr>
<tr>
<td></td>
<td>Discrete phase: escape</td>
<td>Temperature: 20.2 °C</td>
</tr>
<tr>
<td>Return Air</td>
<td>Pressure Outlet</td>
<td>Temperature: 25 °C</td>
</tr>
<tr>
<td></td>
<td>Discrete phase: trap</td>
<td>Pressure: +10.6 Pa</td>
</tr>
<tr>
<td>CO₂ Concentration</td>
<td>Velocity Inlet</td>
<td>Velocity Inlet: 0.18 m/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Exhale: 38,000 ppm [29]</td>
</tr>
<tr>
<td>Bioaerosol</td>
<td>DPM: Injection</td>
<td>Velocity: 1.5 m/s</td>
</tr>
<tr>
<td>Patient</td>
<td>Wall</td>
<td>Flowrate: 0.17 kg/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Particle Size: 1–5 μm, median 2.5 μm</td>
</tr>
<tr>
<td>Surgeon</td>
<td>Wall</td>
<td>Heatflux: 17.45 W/m² [30]</td>
</tr>
<tr>
<td>General Lightings</td>
<td>Wall</td>
<td>Heatflux: 33.55 W/m² [30]</td>
</tr>
<tr>
<td>Operating Lightings</td>
<td>Wall</td>
<td>Heatflux: 288 W/m² [30]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heatflux: 320 W/m² [30]</td>
</tr>
</tbody>
</table>

3.4. Grid Independence Test and Validation

The parameters could change the level of accuracy during the simulation process [30]. Increasing the number of mesh elements influences the accuracy of the simulation results. However, this requires a long time and sufficient resources. The grid independence test and validation of the simulation are illustrated in Figure 4. Three different meshes with 894,474, 1,543,686, and 2,303,385 were generated and simulated to obtain the optimal number of elements that can meet the appropriate meshing process. Furthermore, the grid independence test was validated for accuracy with the field measurement data of temperature and velocity. There were seven temperature measurement points in the field measurements, and then compared with the numerical simulation results. The velocity data were analyzed from the height of 0 m to 3 m. The type of mesh that is closest to the measurement data is 2,303,285 elements. However, it required sufficient resources and time. Therefore, considering the number of 1,543,686 elements with an error of less than 10% could be optimum for the subsequent simulation.

![Figure 4. Grid independence test and validation of the measurement and simulation. (a) Grid independence test; (b) Validation.](image-url)
4. Results and Discussion

4.1. Experimental Results

Field measurement tests were conducted in at-rest occupancy state conditions, and the results were also retrieved in accordance with the operating room standards. The results can represent the operating room quality with the data parameters: ventilation rate, temperature, relative humidity, pressurization, and particle counts. The measurement results revealed that the total air change per hour in this operating room was 22 ACH, which qualifies to the operating room design based on ASHRAE Standard 170 with a minimum of 20 ACH. The other indoor environmental parameters met good agreement with the standard: temperature average of 21.6 °C, relative humidity of 51.4% (shown in Figure 5), and pressurization of 10.6 Pa. The operating room is classified as ISO 7 (class 10,000). According to the field measurement results, particles at size 0.5 μm were counted less than the standard of 352,000 particles/m³, and also the particles at size 5 μm were counted less than 2900 particles/m³. The field measurement points of 2, 4, and 6 are located under the supply HEPA filter, resulting in a lower temperature and fewer particles in contrast to the outer HEPA location.

![Figure 5. Field measurement test results, (a) temperature and relative humidity, (b) particle counts and air velocity.](image)

4.2. Airflow Pattern Distribution

The airflow distribution in these three different cases needs to be reviewed in more detail. This will certainly affect the flow of clean air supplied by the HVAC system through the HEPA filter to reduce the amount of contamination in the operating room. Figure 6 shows the airflow distribution in different schemes. The airflow in case 1 can spread eventually in the room. In contrast to case 2, the addition of patients, personnel, and medical staff in a critical area becomes very influential in the airflow spread. Some airflow that hits the surface of the human body will cause the variation of velocity. Not only that but the airflow also does not appropriately spread at the bottom of the patient’s bed. This is caused by the obstruction of airflow. Overall, the airflow in the room for case 2 can be well distributed, although it has not reached the entire room properly. The HVAC system recirculates the air in the operating room through the return air grilles. Case 3 shows the importance of paying attention to the airflow direction in the room blocked by the medical trolley. Putting a trolley near the return air grille causes the air suction process in the operating room to obstruct. The airflow collides on the top surface of the trolley and makes the air flow in a reverse direction. The air is more turbulent in the room. Therefore, airflow has difficulty reaching areas outside of the critical zone.
4.3. Contamination Removal Analyses in Different Cases

Different cases certainly have different results of concentration. Case 1 analyzes the performance of the HVAC system to reduce the amount of contamination during at-rest conditions. Furthermore, the identification was made in case 2 by adding occupants as a source of contamination in the operating room. Most likely, the amount of contamination is no longer the same as in case 1. However, conditions in the room are not always ideal conditions. Sometimes, health workers put surgical equipment anywhere and, therefore, could block the path of air return. Therefore, case 3 should be examined more comprehensively to determine whether there is a difference from the other cases.

The airflow in the operating room also has a function to dilute contamination. CO₂ was assumed as a source of contamination in the operating room. Figure 7 shows the concentration profile in three different cases. Contamination in case 1 has a low concentration because the contamination could be diluted quickly, and also clean air is evenly distributed in the room (Figure 7a). Case 1 shows a decrease in contamination and is more efficient compared to other cases. This is because the operating room in case 1 was unoccupied and without any medical equipment. In contrast, in case 2, additional patient and surgery personnel generated some contaminants. Concentration increases in case 2 due to the addition of occupants placed in the middle of the room (critical zone) so that the airflow flowing in the room is slightly obstructed (Figure 7b). The air that spreads in the room has a concentration of air exhaled from the patient and surgery personnel. The cross-section from that figure shows the highest concentration is in the ceiling because airflow cannot reach that part. With the object near the air return, it means the dilution of concentration in the room is inhibited so that the concentration in the room is higher than in other cases. In case 3, it can be clearly seen that the top of the trolley has a high concentration value (Figure 7c). The clean airflow causes this area to be obstructed by the object. The results show the differences between the schemes given in the rooms in case 1, case 2, and case 3.

![Image](image_url)

**Figure 6.** The airflow distribution in different schemes: (a) case 1: at-rest condition; (b) case 2: operational condition; (c) case 3: actual condition.

**Figure 7.** The concentration profile in three different cases. Contamination in case 1 has a low concentration value in the ceiling because airflow cannot reach that part. With the object near the air return, it means the dilution of concentration in the room is inhibited so that the concentration in the room is higher than in other cases. In case 3, it can be clearly seen that the top of the trolley has a high concentration value.
In the final condition, case 1 has the lowest concentration level of 404 ppm, case 2 has an average concentration of 420 ppm, and case 3 has a higher concentration than other cases of 474 ppm. This analysis shows that using the ventilation rate of 22 ACH can efficiently reduce contamination in the different operating room cases.

**Figure 7.** The concentration profile in different schemes: (a) case 1: at-rest condition; (b) case 2: operational condition; (c) case 3: actual condition.

### 4.4. Effect of Ventilation Rate on the Operating Room Concentration

The ventilation rate certainly affects the amount of higher or lower concentrations in the operating room. Lower ventilation rates can result in energy savings but concentrations may increase. In contrast, increased ventilation rates produce fewer particles in the operating room but require more energy. Therefore, the optimal ventilation rate must be adjusted to match the energy consumption and concentration. Increasing the ventilation rate does not always result in a lower concentration, but air pattern distribution is one of the essential things. This study investigated an obstruction near the return air grilles by some medical trolleys, resulting in more turbulent airflow patterns. The increase and decrease in ACH number were carried out in this study with 15 ACH, 22 ACH, and 29 ACH, respectively.

Figure 8 illustrates the concentration contamination decay in different schemes that were monitored for 500 s. The results revealed that the air distribution spread eventually in the operating room for case 1 and case 2 with 22 ACH and could remove the contamination. For case 3, objects near the return air grilles made the concentration higher than the others. The average concentration in the operating room with 22 ACH was 474 ppm. Compared to ideal conditions, the result is higher when the medical equipment is located in the wrong area that could obstruct the airflow. In addition, studies with increasing ventilation rates were also carried out in order to result in lower concentrations. The results revealed that when ventilation rates increased to 29 ACH, the concentration became lower and could be reduced to 446 ppm. The concentration is close to case 2 when the operating room is in ideal conditions (no obstruction in the return air grilles).
the ventilation rates or velocity of air supply entering the room cannot be tried by guessing the numbers because velocity is closely related to airflow and the dilution of contamination. Hence, velocity reduction also has a limit. The ventilation rate reduction could be possible for the operating room with at-rest (unoccupied) and ideal conditions.

![Concentration decay effect in different schemes.](image)

**Figure 8.** Concentration decay effect in different schemes.

In order to have some energy saving, the reduction in ventilation rates was conducted in this study with 15 ACH. The average concentration in the room increased along with the reduction in the velocity inlet. The average concentration was 495 ppm. The lack of air distribution causes the dilution of concentration in the area to be inhibited. Reducing the ventilation rates or velocity of air supply entering the room cannot be tried by guessing the numbers because velocity is closely related to airflow and the dilution of contamination. Hence, velocity reduction also has a limit. The ventilation rate reduction could be possible for the operating room with at-rest (unoccupied) and ideal conditions.

### 4.5. Ventilation Efficiency

Ventilation efficiency is the ratio between the contaminant concentration in the occupied spaces and the concentration in the outlet air. It measures how effectively the air present in a space is replaced by fresh air from the ventilation system [31]. The ventilation efficiency is expressed by the Equation (1)

$$
\epsilon = \frac{C_e - C_s}{(C) - C_s} \times 100\% 
$$

where $\epsilon$ is ventilation efficiency, $C_e$ is pollutant concentration at the outlet air, $C_s$ is pollutant concentration at supply, and $(C)$ is the average pollutant concentration in the room.

The ventilation efficiency results are shown in Table 3. The results revealed that case 1 has the highest efficiency because of no concentration generated inside the operating room, while case 2 and case 3 decreased due to the additional personnel inside the operating room and the blocked return air grilles, resulting in lower ventilation efficiency.

**Table 3.** Ventilation efficiency results.

<table>
<thead>
<tr>
<th>Case Study</th>
<th>C (ppm)</th>
<th>Cs (ppm)</th>
<th>Ce (ppm)</th>
<th>Ventilation Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1 (22 ACH)</td>
<td>404</td>
<td>400</td>
<td>403.7</td>
<td>92.50</td>
</tr>
<tr>
<td>Case 2 (22 ACH)</td>
<td>420</td>
<td>400</td>
<td>417.3</td>
<td>86.50</td>
</tr>
<tr>
<td>Case 3 (22 ACH)</td>
<td>474</td>
<td>400</td>
<td>455.2</td>
<td>74.59</td>
</tr>
<tr>
<td>Case 3 (15 ACH)</td>
<td>495</td>
<td>400</td>
<td>465.5</td>
<td>68.95</td>
</tr>
<tr>
<td>Case 3 (29 ACH)</td>
<td>446</td>
<td>400</td>
<td>438.1</td>
<td>82.83</td>
</tr>
</tbody>
</table>
4.6. Bioaerosol Flow Path Model

Several things that can affect the distribution of bacteria-carrying particles (BPCs) are occupancy state condition, ventilation rates, and operating room design and condition. In this study, two different operating room conditions were investigated during the ideal and actual conditions. The bioaerosol particles were injected into the space from the exact location. Particle sizes were 1–5 $\mu$m and median 2.5 $\mu$m. The particles were released for the same amount of time in the simulation. Figure 9 illustrates the results of the different particles birth time of 50 and 300 s in two different conditions.

The model carried out in the ideal condition presents a good flow path of the bioaerosol particles model. Particles’ birth time nodes at 50 s could be faster diluted through the outlet air (Figure 9a). Along with the time period, the airflow distribution could carry the particles reaching almost the ceiling corner (Figure 9c). In addition, the different conditions were conducted to know the effect of the actual condition in the operating room. The placement of the medical equipment was located blocking the outlet air. The bioaerosol particles were injected. The particles spread to the upper corner of the operating room when simulated for 50 s of particles’ birth time, as shown in Figure 9b. It also had deposition particles below the surgical table. The medical table location affects the air pattern and obstructs the

Figure 9. Distribution of bioaerosol particles in the operating room. (a) case 2: particle birth at 50 s; (b) case 3: particle birth at 50 s; (c) case 2: particle birth at 300 s; (d) particle birth at 300 s.
removal flow path to the return air grilles. Considering not to put the medical equipment near the outlet air grilles could make for better particles’ removal.

4.7. Pressurization

In order to maintain the quality of the air in the operating room, it should have sufficient clean air supplied to dilute and remove the airborne contamination generated within the room. Pressurization is critical to the proper functioning of the cleanroom. Thus, the contamination can be prevented during the surgery process. Figure 10 depicts the results of the pressurization in a different scheme. The field measurement was conducted with the pressurization at 10.6 Pa, compared to the numerical simulation with the pressurization of 10.8 Pa, which has been validated, and the results were close to the experimental results. The design specification of the pressure is 5 Pa, and excessive design air supply creates high pressure. This study was conducted in three different models and different ventilation rates. Case 1 had a pressure of 10.8 Pa, followed by case 2 with 11.1 Pa, and case 3 with 10.9 Pa. The difference model conditions in the operating room did not show a significant change in the results of room pressurization. In addition, the different ventilation rates in case 3 made a quite significant change compared to the existing design. The results of operating room pressurization with ventilation rates at 15 ACH, 22 ACH, and 29 ACH were 9.2 Pa, 10.9 Pa, and 13.6 Pa, respectively. Increasing the ventilation rates makes the pressurization higher, but when it decreases, it is still larger than the design requirement minimum at 5 Pa.

![Figure 10. Pressurization effect with different schemes.](image)

5. Conclusions

This research investigates indoor environmental parameters for the operating room through field measurement tests. CFD simulations were also conducted to investigate and analyze the operating room performance in different schemes. The conclusions are as follows:

- The experimental data were retrieved during unoccupied conditions (at-rest), and this condition reached the design specification following ASHRAE 170 standard and ISO 14644.
- The results of concentration contamination and bioaerosol flow path revealed that case 1 presents a good airflow distribution and less particle concentration when unoccupied with the average concentration value of 404 ppm, while case 2 generated a higher concentration while performing a surgery with an average concentration value of...
420 ppm. Then, some medical equipment blocked the outlet air in case 3, resulting in the highest concentration with an average concentration value of 474 ppm.

- Increasing the ventilation rates could result in a lower concentration. Increasing ventilation rates does not always present a good concentration dilution, but the air distribution pattern could also affect it. Some medical equipment is recommended not to block the outlet air grilles for dilution purposes. The average concentration in case 3 with different ventilation rates: 15 ACH, 22 ACH, and 29 ACH were 495 ppm, 474 ppm, and 446 ppm, respectively.

- According to case 1, the ventilation efficiency in case 2 and case 3 dropped around 6% and 17.91%, respectively. Ventilation efficiency also decreased along with decreasing ACH, while with increasing ACH, the ventilation efficiency in the case 3 actual condition increased, approaching case 2 in an ideal condition.

- The blocked return air also affected the bioaerosol distribution that could not be directly removed or diluted through the outlet. It could obstruct the flow path resulting in the airflow distribution that could carry the particles reaching almost the ceiling corner, and even deposited in behind the surgical table.

- The reduction in ventilation could increase the concentration inside the room and would not be possible to implement when the operating room is performing surgery. The reduction also has a limitation that should be met with the design requirements such as temperature, relative humidity, pressurization, and particle counts. It could be implemented during the unoccupied state condition to achieve energy saving.

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