OPTIMAL POSITIONING OF AIR-EXHAUST OPENINGS IN AN OPERATING ROOM BASED ON RECOVERY TEST: A NUMERICAL STUDY

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Sasan Sadrizadeh*, Sture Holmberg

Division of Fluid and Climate Technology, School of Architecture and the Built Environment, KTH Royal Institute of Technology, Stockholm, Sweden

Corresponding author: sasan.sadrizadeh@byv.kth.se

ABSTRACT

This study investigates the influence of outlet location on conventional, turbulent-mixing operating-room (OR) ventilation performance. This was done by numerical simulation using computational fluid dynamics. Multiple configurations of OR outlets, both at floor and ceiling level, were examined, and the results were compared. OR ventilation-system performance in each case was examined by conducting a tracer-recovery test. Two common anesthetic gases, halothane ($C_2HBrClF_3$) and desflurane ($C_3H_2F_6O$), were used to perform the test. Particle simulation was also considered to simulate bacteria-carrying particles.

Based on achieved results, the floor-level exhaust outlets effectively removed anesthetic gases and other odors that might be released in the OR during surgery. Such gases are most likely found at floor level, since they are usually heavier than the air. On the other hand, air-exhaust openings at ceiling level very efficiently evacuated any airborne particles carrying microorganisms, lighter anesthetic gases, or other chemical substances. It is found that floor-ceiling mounted exhaust outlets at every corner of the OR is the optimal arrangement.

KEYWORDS

Hospital operating room, ventilation system, particle distribution, exhaust outlets

1 INTRODUCTION

It is very important to preserve good indoor air quality in the operating room (OR) to ensure health and safety for both surgical team members and the patient. It is well-known that the surgical staff and the patient are the main sources of airborne particles. Human skin is continually being renewed, and the outer skin is shed as squames, or scales. The size distribution of such particles are anywhere between 4 µm and 60 µm, with a mean size of 12 µm in diameter (Noble et al., 1963; Noble, 1975). Microorganisms or bacteria are carried on more than 10 percent of these skin particles, which drift around in the air until they settle down or are evacuated. A substantial amount of anesthetic gases and odors are also released into the OR air from equipment. The highest concentrations of gases during surgery are at floor level. Nevertheless, these gases can be mixed with OR air due to staff movement, and be inhaled by both staff and patient.

The ventilation system of a hospital OR preserves indoor air quality, dilutes and reduces microorganisms concentration to acceptable levels, and removes anesthetic gases and odors released during an operation. OR ventilation-system performance depends on several factors, including type of ventilation system (such as mixing, displacement, or laminar), the air exchange rate, and position of air-exhaust grills (Cao et al., 2014; Kruppa & Ruden, 1996). The air-exhaust openings within ORs vary in size, number and geometry, depending on type of ventilation system and the function of the space. Typically, there should be at least two air discharge outlets inside the OR, usually at floor level. Different studies use different numbers and locations of air-exhaust openings (Chow & Yang, 2003; Chow & Wang, 2012; Sadrizadeh et al., 2014). However, a great deal of care should be given to considering possible airflow obstructions, such as improper positioning of staff members, equipment, and other furniture.

This study assesses and explores the influence of different numbers and locations of air-exhaust openings on OR mixing-ventilation system performance.

Use of commercially available computational fluid dynamics (CFD) tools is now commonplace in the OR design process. Using these techniques, the airflow and temperature distribution in a room can be predicted before the room is built, making it possible to base design decisions on predicted flow conditions.

2 METHOD

A numerical simulation by the CFD technique was performed to investigate the influence of outlet positions on ventilation performance. Three-dimensional airflow and pollutant dispersion were modeled using the RNG k–ε turbulence model, which was numerically solved using the finite-volume method. ICEM CFD was used for grid generation, and double-precision FLUENT 14.5 was used to solve the flow field. The airflow simulation was subjected to grid-sensitivity analysis to find the grid-independent solution.

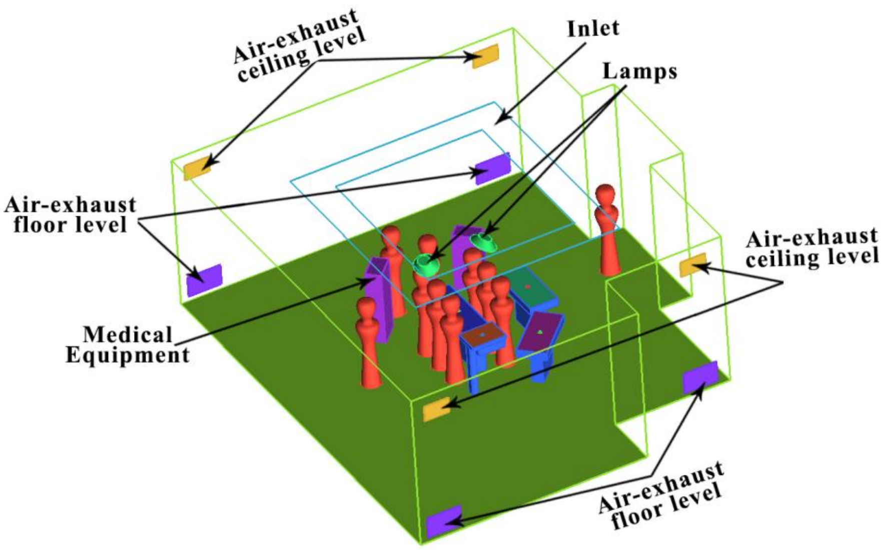

Figure 1: Geometric configuration of operating room and different configuration of air-exhaust outlets

Figure 1 shows the physical arrangement of the OR in this study, based on a Nya Karolinska hospital in Stockholm, Sweden. The overall dimensions were 8.5 m (L) × 7.7 m (W) ×3.2 m (H). Ten surgical staff members, with 100 W/m^2 heat flux, were considered in upright, stationary positions surrounding the patient. In this model, staff members, medical lamps, and equipment were located relative to the operating table, according to the DIN 1946-4 (2008) specification. Incoming air was introduced to the OR at a total airflow rate of 2 m^3/s in a turbulent-mixing flow pattern. Three different configurations of exhaust opening were considered, at both ceiling and floor levels:

- Case 1: Four air-exhaust outlets considered at floor level
- Case 2: Four air-exhaust outlets considered at ceiling level
- Case 3: Eight air-exhaust outlets considered at both ceiling and floor level

The air-exhaust outlets were mounted in every corner of the OR, for a total of four floor and four ceiling exhausts. Bacteria-carrying particles, at a source strength of four colony-forming units (CFUs)/s per person, were simulated in a Lagrangian framework to evaluate transmission risk of airborne particles (Sadrizadeh et al., 2014). Particle-carrying microorganisms, with an aerodynamic diameter of 12 µm, were emitted from staff skin to the OR air. The particle trajectory terminated when particles reached rigid surfaces (trap boundary) or were evacuated from the OR air through the exhaust opening (escape boundary). No recycling from the walls was considered.

2.1 Recovery Test

ISO 14644-3 (14644-3:2005, 2006) describes methods, called *recovery tests*, that show the ability of the OR ventilation system to remove particles and gases. It also states if the OR can change from a dirty to clean state within the specified time. *Recovery time* is the time, in minutes, to decrease particle concentrations by two orders of magnitude (100:1). *Recovery performance* can also be determined from the slope of the particle concentration decay-curve. Cleanliness recovery rate in minute^{-1} is determined by measuring the effect of ventilation on the decay rate of test particles introduced into the OR, calculated from the following:

$$n = \left(-2.3 \times t^{-1}\right) \log\left(\frac{C_1}{C_0}\right) \quad (1),$$

where n is the cleanliness recovery rate (/min), C_0 is the initial concentration, C_1 is the final concentration, and t is the time taken from initial to final concentration.

In this study, based on the German DIN 1946-4 standard (2008), the OR was exposed to 3,500 particles/m^3 of air (0.5 μm). The time taken to reduce the particle concentration by two orders of magnitude (100:1) was then calculated and listed as recovery time.

According to Zhao and Wu (2005), this size of particles can be treated as a passive contaminant. Therefore, to examine the recovery test, we sampled two commonly used gases in anesthetic practice, halothane ($C_2HBrClF_3$) and desflurane ($C_3H_2F_6O$), to perform the tracer-based methodology (Habre et al., 2001).

3 RESULTS AND DISCUSSION

To investigate the effect of numbers and locations of exhaust outlets on the airflow field and particle distribution during surgical procedures, different configurations of exhaust openings were simulated, and results were compared. The steady airflow field was first obtained by steady-state simulation. Convection and diffusion of contaminants within the OR were then modeled by solving conservation equations in transient simulation. Moreover, BCP distribution was examined using Lagrangian particle tracking method.

Figure 2 shows the recovery test result for all three cases. The cleanliness recovery rates respectively were -2.6/min, -3.2/min and -3.5/min for ceiling, floor, and ceiling-floor air-exhaust outlets.

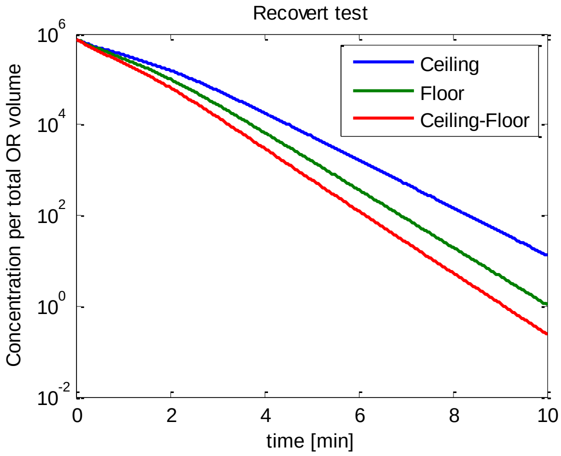

Figure 2: Recovery test results for three different air-exhaust outlet configurations

The lowest possible recovery time was achieved with Case 3 (ceiling-floor exhaust). When the exhaust openings were at both floor and ceiling levels, all the released gases were easily evacuated. Desflurane gas concentration was much higher at the floor-level outlets, since it is heavier than air. Conversely, Halothane concentration was higher at the ceiling level outlets, as it is lighter than OR air.

Figure 3 shows normalized particle concentration contour plots on a vertical plane (x = 1 m) for all three cases. Particle concentration was normalized with outlet concentration. Particle density (ρ = 1000) was much higher than OR air. However, the lowest possible particle concentration was achieved by positioning multiple outlets (ceiling-floor exhaust opening). This layout may contribute to more uniform air movement within the OR. Fewer eddies were generated by the air circulation inside the OR, so particles may not be trapped by such eddies and evacuated from the OR.

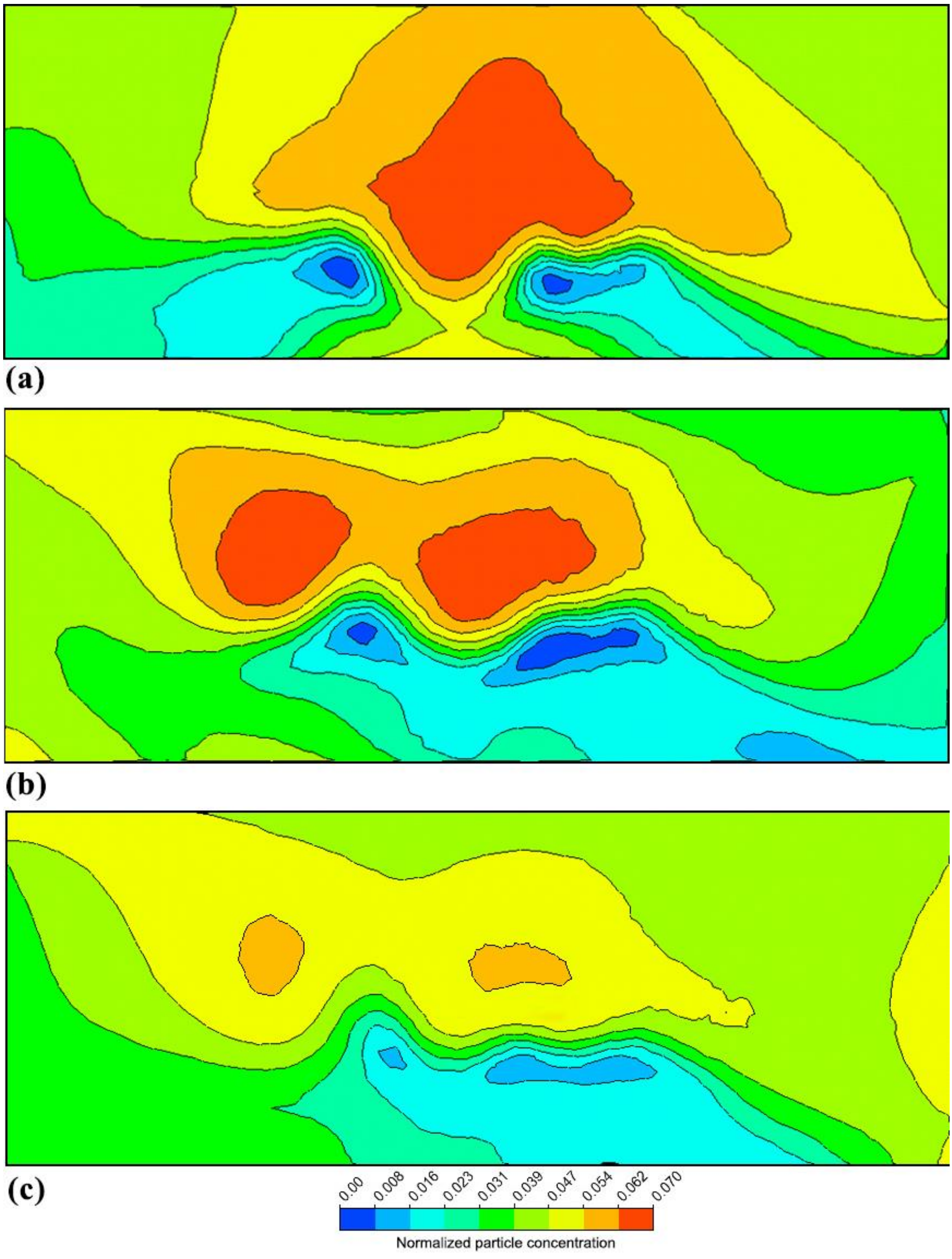

Figure 3: Normalized particle concentration over a vertical plane, x = 1 m . Air-exhaust opening at: **a)** ceiling level, **b)** floor level, **c)** ceiling-floor level

4 CONCLUSIONS

Ceiling-floor exhaust opening had the best performance in terms of recovery-test and particle simulation. This exhaust-mounting strategy achieved the lowest possible particle concentration and shortest recovery time. Positioning multiple air-exhaust outlets inside the OR is highly suggested. Floor-level outlets are more efficient at removing various anesthetic gases and infectious particles that may be heavier than the air. The ceiling exhaust openings that are mounted high on the wall are the most effective at removing any bacteria or other pathogen-containing particles and chemical substances that may become airborne during a surgical procedure. The optimum layout is both ceiling- and floor-height fixed exhausts at every corner of the OR. That makes a total of four floor- and four ceiling-mounted exhausts. This arrangement contributes to a more uniform airflow pattern within the OR. This layout avoids producing big eddies that may trap particles for a long time.

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