Multizone Modeling of Strategies to Reduce the Spread of Airborne Infectious Agents in Healthcare Facilities

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ABSTRACT

Control of airborne infectious agents in hospitals is critical both to effective health care and to the control of direct and indirect health care costs. Current hospital design guidelines focus on ventilation rates, room pressure control and air filtration to control the spread of airborne infectious agents. Studies indicate, however, that there is much variability in hospital design strategies used by engineers to control airborne pathogens. This study focuses on a number of questions concerning current hospital design practices and provides an overview of the tools and methods that can be used to answer some of these questions. Multizone airflow and contaminant transport simulations are used to examine different control strategies and some related issues of design and application. Design issues associated with room pressurization, filtration, and ultraviolet germicidal irradiation (UVGI) are also reviewed. The results provide some important insights into the following issues: 1) using a ventilation flow differential based on building leakage better captures the relevant airflow physics of space pressure control; 2) anterooms can be effective barriers for reducing contaminant transport due to pressure differential disruptions; and, 3) filtration can provide significant protection, with more effective protection provided by additional UVGI systems.

Keywords

Airborne infection, filtration, hospital, indoor air quality, simulation, ventilation

1. INTRODUCTION

Nosocomial infection from airborne infectious diseases continues to be a serious issue in many healthcare facilities. Sandrick [1] estimates that hospital-acquired infections lead to approximately 88,000 deaths and cost upwards of $3 billion a year, of which airborne nosocomial diseases account for 4 % to 5 %. In much of the U.S., health care facility design is based on guidance published by the Facility Guidelines Institute (FGI) [2], which references ASHRAE Standard 170 [3] for ventilation requirements, and by the United States Center for Disease Control (CDC) [4]. Prior to 2010, the FGI guideline was published by the American Institute of Architects (AIA) [5]. ASHRAE also publishes an HVAC design manual for hospitals and clinics [6]. However, the degree to which hospital designs follow these different guidelines is unknown. A survey of twenty hospital designers conducted after the 2001 update to the AIA guidelines suggests that there was little consistency in hospital design strategies to control airborne pathogens [7]. Only half of the twenty mechanical engineers interviewed were required to follow AIA 2001 design guidelines. Those hospitals that were constructed to meet the latest AIA and CDC guidelines were often not monitored to assure correct operation. In a follow-up to the survey, Hermans et al. [8] reviewed ten recent hospital designs and found that contract documents often fell short of the 2001 AIA guidelines or did not provide enough information to determine whether they met the guidelines. These guidelines address room pressure control, minimization of mold growth downstream of humidifiers, testing, adjusting and balancing (TAB) verification, and overall system performance verification or commissioning.

Various modeling studies have addressed the problem of airborne nosocomial infections. Most of these studies have assessed the effectiveness of a particular control strategy on the analysis of a single room [9-15]. Other studies have used a more holistic approach, attempting to

model all aspects associated with the risk of airborne infection [16, 17]. These aspects include identification, isolation and treatment of tuberculosis cases; surgical masks and treatment booths applied at the source; environmental controls such as ventilation, air filtration, and ultraviolet germicidal irradiation; and respiratory protection for susceptible persons.

The present study builds upon the previous works by performing airflow and contaminant transport modeling of a hypothetical hospital to examine some issues related to the referenced design guidelines. The study was also conducted to demonstrate modeling as a tool for assessing the effectiveness of various control strategies. The model employed in this study, CONTAM [18], is a multizone, well-mixed model that provides a highly configurable framework for analyzing airflow and indoor air quality (IAQ) issues. Using the capabilities of CONTAM, the present study investigates the effect of various filtration approaches including ultraviolet germicidal irradiation (UVGI) on airborne contaminant dispersion. Note that this modeling study was conducted prior to the publication of the ASHRAE/ASHE Standard 170 in 2008 [3] and the 2010 FGI guideline [2] so the model assumptions may not reflect these documents.

1.1 Airborne pathogens and their control

Modeling the spread of airborne infectious diseases requires an understanding of how infectious agents are generated, transmitted, and removed. Both the generation and the transmission of airborne pathogens depend on the characteristics of infectious microorganisms. Various approaches are available to remove airborne pathogens, including dilution ventilation,

source control, and pathogen removal. Modeling must also include the transport associated with building airflows, deposition on interior surfaces and other mechanisms.

1.1.1 Characterization of airborne pathogens

The characteristics of infectious agents are a primary consideration in understanding their transport and fate in buildings and when designing control strategies to minimize their spread. Past studies have shown that 99.9 % of all bacteria are removed by 90 % to 95 % dust spot efficiency filters because bacteria are typically present in colonies larger than 1 μm [19]. Kowalski et al. [20] provide an extensive list of pathogens with corresponding logmean diameters, which they contend are more relevant than the mean diameters. ASHRAE has published a position document on airborne infectious diseases that lists 11 diseases spread by droplet or airborne transmission [21]. These contagious respiratory diseases are transported in the form of droplets that are aerosolized through coughing and sneezing [22]. The large droplets settle onto surfaces and aggregate with dust, making them non-respirable. The smaller particles evaporate and form droplet nuclei with a 1 μm to 5 μm average diameter, which allows them to stay airborne [23]. A single sneeze can generate a hundred thousand droplet nuclei with viable pathogens, but little information exists in the literature on how many constitute an infectious dose [22].

In operating rooms, the route of infection from bacteria is generally thought to be through squames, skin scales or particles that are approximately 10 μm in diameter. These bacteria laden particles are emitted from the surgical staff and patient during an operation and can settle onto the surgical site, causing infection [10]. Woods et al. [24] estimated a squame slough rate of

6 µg/min to 12 µg/min in an operating room. Even with emission rates and particle characteristics, patient exposure to viable airborne pathogens is still difficult to model because of the complex mechanisms that control infection risk. In an attempt to incorporate the probability of infection into contaminant models, Nicas [25] used a stochastic model to assign probability values to contaminant exposure.

1.1.2 Control strategies – dilution

Dilution with outdoor ventilation air is the main method for maintaining acceptable indoor air quality in buildings and generally relies on the heating, ventilating, and air conditioning (HVAC) system. Effective dilution of airborne pathogens depends on the air change rate of a room, which refers to how frequently the air is replaced with outdoor or filtered recirculated air. The CDC [4], FGI/AIA [2, 5] and ASHRAE [3, 6] documents provide minimum outdoor air and total (outdoor air plus recirculation) air change rate values for different hospital room types. However, realizing these design rates in practice requires proper commissioning, operation and maintenance to achieve the intended performance over time. The operating characteristics of HVAC systems change over time due to filter buildup, fan belt slippage, ductwork blockage, and various damper problems [26].

High air change rates help remove airborne pathogens, but the systems required to achieve this high level of ventilation are costly and not without drawbacks [27]. Miller-Leiden et al. [28] found that isolation room air change rates above the AIA/CDC recommendation of 12 h^{-1} resulted in airflow patterns that decreased the effectiveness of stand-alone filtration units used in a large test chamber. They suggest that the higher air change rate disrupted the exhaust airflow,

leading to a locally high particle concentration region. Similarly, Woods, et al. [24] measured higher particle concentrations with an air change rate of 18 h^{-1} than with 12 h^{-1} in a room with a ceiling diffuser. High flow rates from the ceiling diffuser prevented contaminants from being lifted out of the zone by disrupting the natural convective currents in the operating room. However, these limited studies require further analysis and validation. Marshall et al. [29] studied ventilation efficiency using tracer gas measurements in a scale model protective isolation room and found the area near the bed to be the most well-ventilated. For operating rooms, the AIA [5], ASHRAE [3] and CDC [4] documents suggest that supply air should come from ceiling outlets near the center of the work area, and return vents should be near the floor.

1.1.3 Control strategies – source control

In the context of airborne infectious agents, source control refers primarily to maintaining pressure differentials between spaces to prevent these agents from migrating between zones. Positively pressurized rooms are designed to protect susceptible patients, and negatively pressurized rooms are designed to isolate contagious patients. Many areas in a hospital are negatively pressured to prevent the spread of infection; airborne infection isolation (AII) rooms are commonly used to house tuberculosis (TB) or other particularly infectious patients [6]. Areas that are designated as clean rooms are positively pressured to prevent contamination through air transfer from adjacent spaces, and protective environment (PE) rooms are designed to house sensitive patients. Pressure differentials are created and maintained using HVAC controls and monitoring. A negatively pressured room is designed to exhaust more air than is supplied, while the reverse is true for a positively pressured room.

The CDC [4], ASHRAE [3] and FGI/AIA [2, 5] documents contain a recommended pressure differential of ±2.5 Pa for pressurized areas, yet this pressure differential is not always maintained in practice. Pavelchak et al. [26] studied 82 isolation rooms in New York hospitals and identified significant problems associated with pressurized rooms; 54 % of the isolation rooms were found to have a doorway airflow direction opposite of the design specifications (into the room). Unbalanced ventilation systems, shared anterooms, turbulent airflow patterns, and control system problems led to the unexpected outward directional airflow. The study also found that of the isolation rooms that had continuous pressure monitors present, 50 % of them indicated pressures opposite in sign to those indicated by a smoke test. This high rate of failure highlights the need for alternative design and analysis tools such as airflow modeling, as well as improved operation and maintenance procedures.

The guidelines also suggest that there should be at least two return air inlets that are separated from each other as far as possible. In all rooms, air should be directed from clean areas to dirty areas. Olsen et al. [15] found that if diffusers are placed to induce clean air, and the exhaust vents are near the patient, then the diffuser type does not strongly affect the distribution of airborne pathogens in the room. Memarzedeh et al. [11] found that laminar flow regimes provide the best airflow distribution in operating rooms because they direct dirty air away from the surgical site. That study also determined that a mixture of exhaust location levels provided the best airflow distribution.

1.1.4 Control strategies – pathogen removal

Filtration is a primary method used in hospitals to remove airborne pathogens. ASHRAE Standard 170 [3] currently requires two levels of filtration for patient rooms other than protective environment rooms: a MERV 7 pre-filter and a MERV 14 secondary filter. Protective environment areas are required by the standard to have HEPA filtration for supply air, corresponding to removal of at least 99.97 % of 0.3 µm particles at the rated flow. Similarly, negative pressure areas that recirculate air (only allowed if rooms are retrofitted from standard patient rooms and it is impractical to exhaust directly outdoors) are required by Standard 170 to have HEPA filtration on the return air inlets. The effectiveness of filtration depends on proper installation and the minimization of filter bypass. Alternatively, stand-alone HEPA filtration units continuously recycle room air to remove pathogens, providing a potentially important, but not required, level of protection. In a series of laboratory tests, Miller-Leiden et al. [28] found that ceiling-mounted HEPA filtration units performed better than portable units, and that non-HEPA units performed as well as HEPA units for two distinct test aerosols: nonviable chemical particles with 0.7 µm median diameter and a geometric standard deviation (GSD) of 2.0, and bacterial particles (from a suspension of *bacillus subtilis*) with 1.3 µm median diameter and a GSD of 1.3 . These findings suggest that cheaper, non-HEPA filters (60 % to 95 % efficient) may be as effective as HEPA filters in some cases. Additionally, Kowalski et al. [20] concluded from modeling results that 90 % efficient filters are nearly as effective as HEPA filters for common spores (typically 1µm and larger), and that the use of HEPA filters in health care facilities may not be necessary especially when UV radiation is also being used. Also, air from

adjacent spaces may be more likely to cause airborne nosocomial infections than clean air from ducts, suggesting that HEPA filters within ducts provide only limited protection [27].

Ultraviolet germicidal irradiation (UVGI) is intended to limit transport of infectious agents from patient rooms in hospitals or lobbies in public access buildings by reducing their airborne levels [6]. There are three types of UVGI systems: irradiation of the upper zones of occupied spaces (called upper-level room), in-duct and in-room. In-duct and in-room UVGI systems may be used in operating rooms or hospital waiting rooms. In-duct UVGI systems use banks of UV lights within the duct system in order to inactivate microbes. Upper-level room UVGI relies on room air motion to transfer pathogens to UV lights that are suspended from ceilings and shielded to prevent UV exposure to occupants. In-room UVGI uses a combination of fans and UVGI in recirculating units. While UVGI has existed for over fifty years, research regarding its effectiveness in health care facilities is still limited and more evaluation and demonstration work is needed. In-room UVGI may offer its greatest potential in patient corridors and hospital waiting rooms where undiagnosed patients could be releasing infectious agents, in particular because UVGI is considerably less expensive than a new mechanical ventilation system and more easily installed [27].

The effectiveness of in-room UVGI depends on the mixing effectiveness of the ventilation system, which determines the cumulative dose of irradiation experienced by the pathogens [27]. Well-mixed room models neglect this important aspect of UVGI system performance; thus, computational fluid dynamics (CFD) programs have been used to obtain a more detailed understanding of their effectiveness. Noakes et al. [14] used both analytical and CFD methods to model UVGI. This study found that multizonal analytical models, which subdivide rooms into vertical levels, can provide zonal concentrations that compare well to CFD simulations. Another

CFD study of UVGI [9] found that UVGI does not kill a significant portion of viable airborne particles. However, the authors felt that the CFD parameters used in the study resulted in an unrealistically high fraction of removal by deposition. High air change rates can also decrease UVGI effectiveness by decreasing particle residence time in the UV zone, as shown in a CFD modeling study done by Memarzadeh et al. [12]. Kowalski et al. [30] define UVGI effectiveness in terms of kill rates, which are comparable to filter efficiencies. In order to model UVGI deactivation of airborne pathogens, the authors assigned URV (Ultraviolet germicidal irradiation Rating Value) to levels of UV intensity, analogous to MERV filter ratings. The URV and MERV removal fractions for several airborne pathogens were computed and combined, creating a single MERV/URV removal efficiency. For example, a pathogen removal system that employed an URV8 UVGI system with a MERV 8 filter was assigned a removal efficiency of 0.19 for influenza [30]. Further study of UVGI is still needed to understand its effectiveness and to develop engineering design guidance.

Antimicrobial duct coatings and air filters have also been used to combat the spread of airborne infectious diseases, but their effectiveness is unclear. Foarde et al. [31] found that two of the three tested antimicrobial sealants limited the re-growth of fungal contamination in a laboratory experiment. The study also noted that different antimicrobials are not equally effective on all microorganisms and suggested antimicrobial duct coatings should be tested and marketed for a specific set of microbes. Cecchini et al. [32] applied antimicrobial agents directly to air filters and found good compatibility with only some of the air filters tested. The study also found that filters support microbial growth, yet a similar study by Foarde and Hanley [33] found that under normal use conditions, filters are not likely to become a source of microbial contamination. They also found that antimicrobial agents were ineffective on dust-loaded filters.

Because of the limited availability of research data on the effectiveness of antimicrobial agents on airborne pathogens, the control strategies that employ these agents cannot be accurately modeled at this time.

1.2 Scope of study

This study investigates a number of questions related to hospital design practices in North America and provides a demonstration of simulation methods that can be used to answer some of these questions. The simulation results should be considered examples of the types of results that may be obtained but should not be considered as recommendations for the design of any specific facility. The risk associated with different control strategies depends on the extent of contaminant transfer, which in turn depends on the interzone leakage pathways and pressure differentials, all of which are a function of the design and operation of a specific building. Steady state airflow analysis allows a designer to view pressure differentials and airflows through air leakage pathways. Transient airflow analysis, allows a designer to consider more realistic operating conditions, such as: doors being opened and closed, air supply rates changing, and varying weather conditions.

The objective of the present study is to examine how zonal contaminant concentrations and pressure differentials across important boundary flow paths are affected by several transient factors that are described in the section 2.3 on simulation design. To this end, a set of multizone modeling simulations of a generic health facility were conducted to explore the effects of normal building activities on interzone pressure differentials. Transient zonal contaminant

concentrations are also predicted for each steady-state flow simulations in order to investigate time-varying contaminant transmissions. Finally, the effects of various filtrations with HEPA and UVGI on contaminant removal are examined.

2. Simulation methodology

The simulations were conducted in two phases. The first phase involved the creation of a baseline model. The second phase involved changing individual flow elements in the baseline model (i.e., door positions, supply/return flows) in order to determine the nature and magnitude of airflow and contaminant concentration changes for the different scenarios.

2.1 Multizone modeling

There are three general types of computer simulation techniques for studying airflow and contaminant transport in buildings – field, zonal and multizone modeling. Field modeling, based on computational fluid dynamics (CFD), takes a microscopic view of airflow and contaminant concentrations to predict the detailed flow fields and pollutant concentration distributions within a room or rooms [34]. Zonal modeling takes an intermediate view of airflow and contaminant transport by dividing a room into sub-zones [35, 36]. Multizone (or room network) airflow and pollutant transport modeling [18, 37, 38] takes a macroscopic view by evaluating average pollutant concentrations in the different zones of a building as contaminants are transported through the building and its HVAC system. To identify the impact of changing ventilation and building characteristics for an entire hospital, a multizone model was selected for this study.

The multizone approach is implemented by constructing a building model as a network of elements describing the flow paths (HVAC ducts, doors, windows, cracks, etc.) between the zones of a building. The network nodes represent the zones, which are modeled at a uniform pressure, temperature, and pollutant concentration. After calculating the airflow between zones and the outdoors, zone pollutant concentrations are calculated by applying mass balance equations to the zones, which may contain pollutant sources and/or sinks. The program CONTAM [18] was utilized for the multizone modeling.

The airflow through leakage paths was related to the pressure difference by the following equation, which is provided in the ASHRAE Fundamentals Handbook [39],

$$Q_r = C_D A_L \sqrt{\frac{2\Delta p_r}{\rho}} \quad (1)$$

where Q_r is the differential flow rate (m^3/s), C_D is the discharge coefficient (assumed to be 1), A_L is the effective leakage area (m^2), Δp_r is the reference pressure difference (4 Pa), and ρ is the density of air (1.204 kg/m^3 at 20 °C).

2.2 Building description

The simulations were based on a hypothetical and generic one-story hospital, which was used to create a baseline CONTAM model that served as the control scenario for the airflow and contaminant transport modeling. This building is not necessarily a realistic hospital, but it does contain many of the building and HVAC system features of interest in demonstrating the

application of the model. The main floor of the baseline model, as represented in the CONTAM interface, is shown in Figure 1. The interior walls for the corridors (C), protective environment (PE), airborne infection isolation (AII), and operation rooms (OR) extend through the plenum space. Regions of interest in the present study are marked by dashed lines in Figure 1. Appendix A provides a detailed listing of the leakage paths and air leakage elements for one of the airborne infection isolation rooms.

2.2.1 Baseline model

According to a survey [7], hospital HVAC designers rely on either fixed or percentage-based flow differentials to achieve desired pressure differentials, but don't consider the effective leakage area of building walls and partitions as a design consideration. The supply flow rates in the baseline model were set based on typical design practice and the return airflow rates were then determined to achieve the desired pressure differentials based on the total room effective leakage areas. Neutral rooms were designed to be slightly positive in order to achieve an overall positive building pressure. Ambient temperature was held constant at 20 °C, while the baseline wind speed and direction were 5 m/s and 180° (north to south), respectively.

The baseline model includes three simple air-handling systems: a system for the exhaust air, a system for the operating rooms, and a system for all the other zones. Both of the air-handling systems that supply air include a MERV 8 filter. The filter efficiency curves were obtained from Kowalski and Bahnfleth [22]. It was assumed that the air cleaning strategies do not impact the pressure differentials when airflow openings or HVAC flows are changed.

2.2.2 Contaminant source

Two types of sources were used in the models: (1) a burst source of 500,000 particles with a diameter of 0.64 μm, intended to represent a tuberculosis-like particle and (2) a constant source of particles at 10 μg/min with a diameter of 10 μm, intended to represent squame cells. The burst source was chosen to be similar to tuberculosis because it represents a realistic contaminant problem in hospitals and falls within a size range (0.05 μm to 1 μm) corresponding to low removal efficiencies for many common particle filters [22]. The constant source was used to represent a steady release of squame particles from the surgical staff. The magnitude of the source was set artificially high in order to ensure significant contaminant transfer could be seen in the model results. If the room of interest was positively pressurized, the burst source was placed in the adjacent corridor. If the room of interest was negatively pressurized, the burst source was placed inside the room. Operating rooms were simulated using both types of contaminant sources: an outside tuberculosis-like burst source and an inside squame-like constant coefficient source.

2.3 Simulation design

A set of simulation scenarios was designed to examine how zonal contaminant concentrations and pressure differentials across important boundary flow paths are affected by:

- a constant flow differential between supply and return airflows, based on median values of flow differentials reported for AII rooms (including adjacent toilet rooms) and ORs in the survey [7]
- the state of the bathroom door (open or closed), assuming there is a constant exhaust flow in the toilet room
- an open door to the corridor
- an increase in the wall leakage area between pressurized zones
- the presence of an anteroom
- cascading pressure differences (i.e. OR > sterile core > outer corridor)
- five different steady-state weather (wind speed and direction) scenarios

The following air cleaning systems are examined:

- MERV 15 filters in all rooms with supply points
- HEPA filters on the supply points
- UVGI systems
- Standalone HEPA filters
- A combination of lower air change rate (baseline value reduced by 2 h^{-1}) and in-room filtration

The specialized rooms (PE, AII, and OR) were the focus of this analysis. For each simulation, one element of the model was altered or added, and pressure differentials and steady state contaminant concentrations were analyzed. Descriptions of the simulations are listed in

Table 1. UVGI systems are difficult to model because there is little testing data available. In-room UVGI is dependent on the flow patterns within the space and the amount of time a parcel of air stays in contact with the light source.

3. Simulation results and analysis

The simulations described in section 2.3 were conducted to investigate the effect of the building and system variations on pressure differentials and/or contaminant concentrations. Table 2 shows the predicted pressure differentials from the specialized rooms, (i.e., PE, AII, and OR) to their adjacent spaces. Negative pressure differentials correspond to air flowing into the listed space, and positive pressure differentials correspond to air flowing out of the listed space. The subscript of ΔP denotes the adjacent space. For instance, ΔP_{TR} for PE1 represents the pressure in PE1 minus the pressure at the toilet room (TR) in PE1. Symbolic representations for each space are given in Figure 1.

3.1 Leakage-based vs. fixed flow differentials

The effect of two design strategies on the pressure differentials were investigated in six different rooms. Table 2 shows that the baseline model with the flow differential based on leakage areas (Case 1) predicted differential pressures that more consistently met the target of 2.5 Pa that is recommended in the guidelines discussed earlier [2-5] compared to the model based on a fixed flow differential (Case 2). The flow differentials in the fixed and calculated flow differential models used the same supply flows but different return flows. For the fixed-flow differential case, many of the pressure differentials were below the target, as low as 0.19 Pa

for OR1 relative to sterile corridor 1 (SC1). These results emphasize that there is a significant potential for design errors and performance problems when using fixed-flow differentials, which is evident in Pavelchek et al. [26]. Additionally, the results for Case 1 show that for some configurations, adjacent spaces (i.e., AII1 next to AII2 and OR1 next to OR2) may not maintain the desired pressure control without a buffer space. These results stress the importance of considering leakage in achieving design pressure differentials.

3.2 Door openings

When the bathroom door is opened, pressure differentials are disturbed slightly in the main rooms and more significantly in the toilet rooms (ΔP_{TR}=0 for PE and AII rooms) as shown in Table 2. To see the influence of the bathroom door opening on contaminant transport, burst sources of 500,000 particles representing a tuberculosis-like particle (denoted by TB hereafter) are modeled in each AII room. Figure 2 shows that when the bathroom door is opened (Case 3), initial TB concentrations are higher than in the baseline model (Case 1). This is because the AII toilet rooms are opened to the source in the parent AII room. A peak TB concentration for each case occurs at approximately 250 s after the burst in AII rooms. TB concentrations are reduced to up to 5 % of the peak concentrations and 0.01 % of the initial concentration within 30 minutes. Additionally, these disruptions did not lead to increased TB concentration in other zones.

Opening the door to the corridor (Case 4) has significant effects on interzonal pressures. Table 2 shows that when AII2 is depressurized with respect to the corridor, a large pressure gradient develops at the boundary of the adjacent AII1, while the pressure gradient to the adjacent normal bedroom (NB) is severely diminished. This result highlights the complications

and potential hazards associated with adjacent pressure-controlled spaces. In general, a door to a pressurized zone will not be left open for more than a few seconds; however, even that can induce a change in contaminant concentrations. To see the effect of the transient opening of a door to the corridor on contaminant transport, a burst source of a TB-like particle is modeled in AII2 and the corridor door is opened for 5 s at t = 630 s after the contaminant burst. Figure 3 shows the transient TB concentration results in the AII2 suite for Cases 1 and 4. Since the TB source is located within the AII2 room, opening a door to the corridor causes a slight decrease in TB concentration, as shown in the inset of Figure 3. However, Figure 4 shows that the TB concentration rises in the adjacent AII1 suite because of the large pressure differential that develops between the two rooms. The large pressure gradient forces TB particles out of the AII2 suite and into the AII1 suite.

3.3 Increasing interior wall leakage area

As expected, increasing the leakage area of interior walls decreases the pressure differentials observed for those boundaries relative to the baseline case. The type and location of the adjacent spaces determine to what extent increasing the interior wall leakage area will affect the pressure differentials and contaminant concentrations. Table 2 clearly shows a negative effect of decreased wall tightness for the protective environmental rooms (PE1 and PE2). For example, increasing the wall leakage (Case 5) reduces the pressure gradient between the PE1 and NB1 from 3.91 Pa in the baseline model (Case 1) to 1.47 Pa, which is below the design target (2.5 Pa). Similarly, the increased leakage reduces the pressure differential between OR2 and SC2 from 3.16 Pa to only 0.88 Pa.

3.4 Effectiveness of anterooms

Anterooms are intended to prevent disruptions of pressure differentials due to door openings and to dilute the air exchanged with the corridor. To examine the effectiveness of anterooms, the results for Cases 4 and 6 were compared with those for the baseline model. Table 2 shows that when the anteroom door is opened to the corridor (Case 4), the pressure differential between the anteroom and the pressurized zone (PE2) increases to provide a pressure barrier. The pressure differential, ΔP_A at PE2 increases from 1.19 Pa for the baseline model to 3.92 Pa for Case 4. However, when the anteroom door is opened to the room (Case 6), the pressure differentials within the room stay at more desirable levels. This result suggests that properly configured anterooms can be effective in maintaining proper pressure differentials within pressurized zones.

To examine the impact on contaminant dispersion of opening an anteroom door, a TB burst source is placed outside of the PE rooms (i.e., in bed ward corridor). Figure 5 shows that opening either the outer or inner anteroom door (Case 4 and 6, respectively) causes no significant TB concentration shifts inside the PE2. However, opening the outer anteroom door (Case 4) does raise the TB concentration within the PE2 toilet room. When the outer door to the anteroom is opened, another section of the toilet room becomes exposed to the TB source in the corridor, leading to the increase of TB concentration in the toilet room.

3.5 Wind conditions

In addition to the baseline weather condition (a wind speed of 5 m/s and direction of 180°), four other simulations were performed at combinations of 1 m/s and 10 m/s wind speeds and

180° (north to south) and 270° (east to west) wind directions, as listed in Table 1 (Cases 7 to 10). Table 2 shows that these changes did not produce large interior pressure changes, with the exception of the Case 10 with a 10 m/s easterly wind speed. An easterly flow is induced within the building, leading to a 71 % reduction in pressure differential on the door of PE1 (ΔP_C at PE1), from 4.33 Pa to 1.25 Pa. Similarly, in AII1, the anteroom door pressure differentials (ΔP_A at AII1) are reduced nearly 50 %, leaving these spaces more susceptible to contaminant transfer. Variable weather can reduce pressure differentials to unacceptable levels, highlighting the importance of continuous pressure monitors in protective environment and airborne infection isolation rooms. While the present study focused solely on steady state weather conditions, it might be worth investigating the effect of more realistic transient weather scenarios including the effect of outside temperature changes on the interior pressure differentials and contaminant transport.

3.6 Air cleaning strategies

ASHRAE's hospital design manual [6] recommends a MERV 14 filter with a MERV 7 pre-filter in all areas for inpatient care, treatment, and diagnosis, with the addition of HEPA filters in protective environment rooms. To examine the effectiveness of filtration in reducing contaminant concentrations, the TB concentrations in PE1 for the different filters are shown in Figure 6. The MERV 8 baseline filter is compared with MERV 15 and HEPA filters (chosen based on the previous AIA guideline). Initially, the TB burst source was released in the bed ward corridor. Within one hour, the MERV 15 and HEPA filters significantly reduce the TB

concentration in the PE1 by about 99 % and 99.99 %, respectively, demonstrating that the HEPA filtration more effectively eliminates the TB contaminant than the MERV 15 filtration.

Ultraviolet germicidal irradiation can be used in almost any area of the hospital, but is often used within ducts or within sensitive areas like operating rooms or protective environment rooms. On the other hand, stand-alone HEPA filters are often used to supplement existing air handling system filtration. Supplementary filtration may also be used in these sensitive areas. Thus, additional standalone HEPA filtration units can be used in patient waiting areas, just as a UVGI system would be used. To analyze the potential effectiveness of the UVGI and standalone HEPA filtration system for a worst case situation of a dirty room next to a sterile space, a TB source is modeled in the distribution room (DR), with the resulting TB concentration shown in Figure 7. Since the released TB disperses in the DR and other spaces, the TB concentration decay over time can be modeled as

$$C(t) = C_0 \exp(-\lambda t) \tag{2}$$

where C_0 is the initial concentration and λ is the decay constant estimated by regression of the TB concentration during the first 10 minutes of the decay. For the baseline case, the decay constant is found to be $\lambda = 7.17\,\text{h}^{-1}$. When the MERV 15 and HEPA filters are applied, a faster decay of the TB concentration is observed ($\lambda = 8.00\ \text{h}^{-1}$), but the HEPA filter does not offer any better performance than the MERV 15 filter because the source is within the room. In addition to the MERV 15, an in-room UVGI system is modeled for further reductions in the TB concentration. The efficiency of the simulated UVGI system is 0.995, and is modeled as a standalone unit with a URV 16 rating for TB [30]. The UVGI system with the MERV 15

increases the TB concentration decay rate to $\lambda = 26.5$ h^{-1}, which is the most significant impact seen. A standalone HEPA filtration system with a flow rate of 142 L/s (300 cfm) is also modeled for further reducing the TB concentration. The standalone HEPA system provides a more modest TB reduction with a decay constant $\lambda = 9.61\, h^{-1}$. This implies that the standalone HEPA filtration or UVGI system has potential for removing the contaminants. However, it should be noted that the reduction rates are going to be pathogen-dependent, which is not accounted for in the model.

Higher air change rates lead to better contaminant dilution, but will result in increased HVAC installation and operation costs. It is important to investigate whether the air cleaning strategies can provide a reasonable contaminant removal efficiency with a lower air change rate in order to save installation and operation costs. The distribution room (DR) and operation room 1 (OR1) are chosen to examine the combinations of decreased air change rate and increased filtration efficiency. Both of the spaces require supply flows of approximately 472 L/s (1000 cfm). A decrease in the air change rate from 6 h^{-1} to 4 h^{-1} is modeled, and Figure 8 shows a slower decay of $\lambda = 6.47$ h^{-1} for the case of reduced air change rate, compared to the baseline case of $\lambda = 7.17\, h^{-1}$. Adding a MERV 15 filter slightly increases the decay rate of the TB concentration for the reduced air change rate case, with the decay constant of $\lambda = 7.07$ h^{-1} comparable with that in the baseline case. In order to obtain TB concentrations that correspond to the AIA Guidelines recommended room design (baseline case), a stand-alone HEPA filtration system would need to be added. With a 142 L/s (300 cfm) stand-alone HEPA filtration system in the reduced air change case, the decay rate of $\lambda = 8.69$ h^{-1} is comparable to that in the baseline case with a MERV 15 or HEPA filter ($\lambda = 8.00$ h^{-1}). As expected, the UVGI system also shows faster decay of the TB concentration under the reduced air change case, and the decay constant of $\lambda = 25.6$ h^{-1} is comparable to that in the baseline case with the UVGI system.

The constant squame source (10 µg/min) was modeled in OR1 and Figure 9 shows that the steady-state concentration for the reduced air change rate is significantly higher than in the baseline case regardless of the filter type. Also, there is no significant difference between the effectiveness of the MERV 15 and the HEPA filter. This indicates that improving filtration under reduced air change rates would not result in a more efficient design.

4. CONCLUSIONS

Current HVAC design guidelines for hospitals offer strategies intended to reduce the risk associated with airborne infectious agents; however, not enough emphasis is placed on the importance of building leakage and the impacts of actual system operation. Multizone airflow simulation is an effective method for examining the effects of normal building and system changes on pressure differentials and contaminant concentrations. Such simulations can be very useful for hospital designers and operators, highlighting the importance of building leakage and weather on the overall performance and effectiveness of the hospital HVAC system. The simulations in this paper serve as a demonstration of the potential application of such tools to the unique and challenging problems of designing healthcare facilities. While these simulations do not necessarily provide definitive answers to specific design problems, they do provide some insights into several issues as discussed below.

- Fixed flow differentials ignore leakage areas from room to room, leading to pressure differentials that are potentially insufficient. This result indicates that better estimates of flow differentials across zonal boundary are needed. Calculated flow differentials based on

building leakage (Eq. (1)) better capture the airflow physics involved and may therefore provide more effective design values for zone supply and return flow rates.

- Toilet rooms are a negative pressure space that can affect zone pressure differentials when opened to the patient room. While this scenario is very common and does not significantly affect pressure differentials at regions of interest, the simulations provide a clearer understanding of this common event.
- When the boundary between two differently pressurized zones is broken (i.e. a door is opened), the desired differential pressure is lost. Thus, when the door of a pressurized zone is opened to the depressurized corridor, the zone is effectively depressurized. This depressurization results in contaminant transfer through the door. Additionally, pressure differentials will also change for boundaries to other adjacent spaces—increasing, decreasing, or changing the direction of the pressure differential. If the direction changes, the protective benefits of the pressurized room are compromised, leading to contaminant transfer between zones.
- Increasing the magnitude of the interior wall leakage can significantly affect contaminant transfer, depending on the extent of the increase and the pressure in each adjacent zone. Typically, increasing the wall leakage will decrease the pressure differential across that boundary. According to the present simulation study, when the interior wall leakage increases by a factor of five, the pressure differential decreases by roughly a factor of two.
- Anterooms are not required for airborne infection isolation rooms or protective environment rooms by current guidelines (except for combination AII/PE rooms), but can offer significant protection from contaminant transfer from pressure differential disruptions. Anterooms are especially effective when two airborne isolation rooms are adjacent to one another.

- Weather conditions can reduce pressure differentials to unacceptable levels, highlighting the importance of considering a range of ambient conditions during design and the potential use of continuous pressure monitors in protective environment and airborne infection isolation rooms.
- Various filtration systems can provide significant protection over contaminant dispersion. The simulations show that HEPA filtration or MERV 15 filtration provide significant protection. Additional stand-alone HEPA filtration or UVGI system may offer additional protection.

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References

[1] Sandrick K. Clearing the air. Health Facilities Management 2001;14:16-20.

[2] FGI. Guidelines for Design and Construction of Health Care Facilities. Facility Guidelines Institute; 2010.

[3] ASHRAE. ANSI/ASHRAE/ASHE Standard 170 Ventilation of Health Care Facilities. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.; 2008.

[4] CDC. Guidelines for environmental infection control in health-care facilities: recommendations of CDC and the healthcare infection control practices advisory committee (HICPAC) Morb Mortal Recomm Rep 2003:52 (RR-10):1–48.

[5] AIA. Guidelines for Design and Construction of Hospital and Health Care Facilities. The American Institute of Architects press; 2001.

[6] ASHRAE. HVAC design manual for hospitals and clinics. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.; 2003

[7] Hewett MJ. Hermans RD. Strategies to reduce the spread of airborne infections in hospitals: Survey of design practice. NIST GCR 05-883; 2006.

[8] Hermans RD. Hewett MJ. Colsch C. Strategies to reduce the spread of airborne infections in hospitals: Review of recent hospital designs. NIST GCR 06-887; 2006.

[9] Memarzadeh F. Jiang J. Methodology for minimizing risk from airborne organisms in hospital rooms. ASHRAE Trans 2000; 106:731-47.

[10] Memarzadeh F. Manning AP. Comparison of operating room ventilation systems in the protection of the surgical site. ASHRAE Trans 2002; 108(2):3-15.

[11] Memarzadeh F. Manning A.P. Reducing risks of surgery. ASHRAE J 2003; (2):28-33.

[12] Memarzadeh F. Jiang Z. Xu W. Analysis of efficacy of UVGI inactivation of airborne organisms using Eulerian and Lagrangian approaches. ASHRAE IAQ; 2004.

[13] Memarzadeh F. Olmsted RN. Bartley JM. Applications of ultraviolet germicidal irradiation disinfection in health care facilities: Effective adjunct, but not stand-alone technology. Am J Infect Control 2010; 38(5): S13-24.

[14] Noakes CJ. Beggs CB. Sleigh PA. Modelling the performance of upper room ultraviolet germicidal irradiation devices in ventilated rooms: comparison of analytical and CFD methods. Indoor Built Environ 2004;13:477-88.

[15] Olsen EL. Kosik WJ. A new method for patient isolation room air distribution design. ASHRAE IAQ; 2004.

[16] Nazaroff WW. Nicas M. Miller SL. Framework for evaluating measures to control nosocomial tuberculosis transmission. Indoor Air 1998;8:205-218.

[17] Nicas M. Nazaroff WW. Hubbard A. Toward understanding the risk of secondary airborne infection: emission of respirable pathogens." J Occup Environ Hyg 2005;2:143-154.

[18] Walton G. Dols WS. CONTAM user guide and program documentation. NISTIR 7251, National Institute of Standards and Technology, Gaithersburg, MD; 2010.

[19] Balaras CA. Argiriou AA. Dascalaki E. Gaglia A. HVAC Systems and Indoor Conditions in Hellenic Hospital Operating Rooms. ASHRAE Trans. 2002; 108

[20] Kowalski WJ. Bahnfleth WP. Whittam TS. Filtration of airborne microorganisms: modeling and prediction. ASHRAE Trans 1999;105:4-17.

[21] ASHRAE. ASHRAE Position Document on Airborne Infectious Diseases. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.; 2009.

[22] Kowalski WJ. Bahnfleth WP. Airborne respiratory diseases and mechanical systems for control of microbes. HPAC Eng 1998;70:34-48.

[23] Bates JH. Nardell E. Institutional control measures for tuberculosis in the era of multiple drug resistance. Chest 1995;108:1690-710.

[24] Woods JE. Braymen DT. Rasmussen RW. Reynolds GL. Montag GM. Ventilation Requirements in Hospital Operating Rooms—Part I: Control of Airborne Particles. ASHRAE Trans. 1986; 92.

[25] Nicas M. Markov modeling of contaminant concentrations in indoor air. AIHA J 2000;61:484-491.

[26] Pavelchak N. DePersis RP. London M. Stricof R. Oxtoby M. DiFerdinando G. Marshall E. Identification of factors that disrupt negative air pressurization of respiratory isolation rooms." Infect Control Hosp Epid 2000;21:191-5.

[27] Beggs CB. Donnelly JK. Kerr KG. Sleigh PA. Mara DD. Cairns G. The use of engineering controls to disinfect mycobacterium tuberculosis and airborne pathogens in hospital buildings. Indoor Built Environ 2000; 9:17-27.

[28] Miller SL. Lobascio C. Nazaroff WW. Effectiveness of in-room air filtration and dilution ventilation for tuberculosis infection control. J Air Waste Manage Assoc 1996;46:869-82.

[29] Marshall JW. Vincent JH. Kuehn TH. Brosseau LM. Studies of ventilation efficiency in a protective isolation room by the use of a scale model. Infect Cont Hosp Epid 1996;17(1): 5-10.

[30] Kowalski WJ. Bahnfleth WP. Musser A. Modeling immune building systems for bioterrorism defense. J Arch Eng 2003;9:86-96.

[31] Foarde KK. Van Osdell DW. Menetrez MY. Investigation of the potential antimicrobial efficacy of sealants used in HVAC systems. J Air Waste Manage Assoc 2001;51:1219-26.

[32] Cecchini C. Verdenelli MC. Orpianesi C. Dadea GM. Cresci A. Effects of antimicrobial treatment on fiberglass-acrylic filters. J Appl Microbio 2004; 97:371-7.

[33] Foarde KK. Hanley JT. Determine the Efficacy of Antimicrobial Treatments of Fibrous Air Filters. ASHRAE Trans 2001;107:156-70.

[34] Li Y. Nielsen PV. CFD and ventilation research. Indoor Air 2011; 21:442-453.

[35] Inard C. Bouia H. Dalicieux P. Prediction of air temperature distribution in building with a zonal model. Energ Buildings 1996; 24(2):125-132

[36] Haghighat F. Li Y. Megri A. Development and validation of a zonal model – POMA. Build Environ 2001; 36(9):1039-1047

[37] Ng L. Musser A. Persily AK. Emmerich SJ. Indoor air quality analyses of commercial reference buildings. Build Environ 2012;58:179-187.

[38] Wang L. Emmerich SJ. Persily AK. Lin CC. Carbon monoxide generation, dispersion and exposure from indoor operation of gasoline-powered electric generators under actual weather conditions. Build Environ 2012;56:283-290.

[39] ASHRAE. 2007 ASHRAE Handbook—HVAC Applications, Ch. 7, Health Care Facilities. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.; 2007.

Appendix A: Flow Element Details

Figure A-1 is a generic diagram of a room and the associated leakage elements. Table A-1 lists the data associated with the generic or specialized leakage elements. The model was designed to allow for different wall and door leakage values for specialized spaces; however, these values were set to generic values for this primary iteration of the project. Generally, each zone in the model has three leakage elements: walls, ceiling, and doors. Leakage through exterior walls was represented by three identical leakage elements at three different relative elevations (0.6 m, 1.2 m, and 1.8 m). If the room is specialized (PE, AII, or OR), then each door is represented by two elements instead of one: an open-door element and a closed-door element that are controlled by schedules. In Figure A-1, a set of three flow elements represents an exterior wall leak, a set of two flow elements represents a door leak, and a standalone flow element represents an interior wall leak.

Table A-1: Leakage element values ($C_D = 1$, $\Delta p_r = 4$ Pa)

Description	Value	Units	Location
Generic leakage element			
exterior wall, typical value	5	cm^2/m^2	
interior wall, typical value	6	cm^2/m^2	
interior door, open	21000	cm^2	
interior door, normal room	129	cm^2	
exterior door	50	cm^2	
tile ceiling	8.68	cm^2/m^2	
garage roof, typical value	1.8	cm^2/m^2	
Specialized leakage element			
interior AII wall	2.78	cm^2/m^2	AII Rooms
interior door, AII room	129	cm^2	AII Rooms
interior door, OR	129	cm^2	OR Rooms
interior door, PE room	129	cm^2	PE Rooms
double exterior door	22	cm^2/m^2	Receiving Room (East Wall)
double interior door	258	cm^2/m^2	Receiving Room (South Wall)

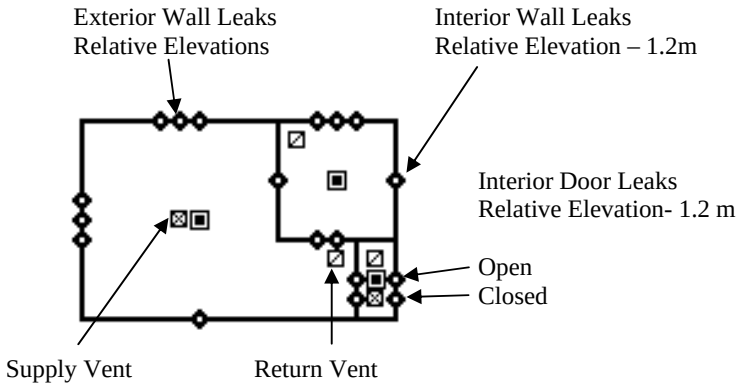

Figure A-1: Generic leakage element diagram (PE Room 2 shown here)

Table 1: Description of simulation cases

Case	Descriptions	Details
1	Baseline	Each of the pressurized spaces analyzed is intended to maintain a pressure differential of 2.5 Pa (0.01 in. w.g.) with adjacent spaces. This control scenario uses supply/return flow differentials based on the sum of the actual leakage areas in the room. The weather condition is a wind speed of 5 m/s with direction of 180°. MERV8 filter.
2	Fixed flow differentials	Fixed supply/return flow differentials of 71 L/s (150 cfm) for AII and PE rooms and 106 L/s (225 cfm) for ORs regardless of the specific room leakage area.
3	Door to toilet room open	The toilet door for each PE and AII room is opened while other toilet doors are closed.
4	Door to corridor open	All of entrance doors in PE, AII and NB rooms are opened to the bed ward corridor. In particular, the outer anteroom doors in PE2 and AII1 rooms are opened to the corridor.
5	Increased wall leakage	Interior wall leakage of room (including toilet and anteroom walls) increased by factor of five.
6	Door to anteroom open	Inner anteroom doors in PE2 and AII1 rooms are opened to the rooms.
7-10	Impact of wind	Case 7: a wind speed of 1 m/s with direction of 180° Case 8: a wind speed of 1 m/s with direction of 270° Case 9: a wind speed of 10 m/s with direction of 180° Case 10: a wind speed of 10 m/s with direction of 270°
11-19	Air cleaning strategies	Case 11: MERV 15 filters in all rooms with supply points Case 12: MERV 15 filters in all rooms with supply points and HEPA filters are used in PE rooms. Case 13: MERV 15 filters in all rooms with supply points and HEPA filters are used in PE rooms. Case 14: MERV 15 filters in all rooms with supply points and UVGI system is used in DR. Case 15: MERV 15 filters in all rooms with supply points and a standalone HEPA system is used in DR. Case 16: A lower air change rate (baseline value reduced by 2 h^{-1}) is applied to DR and OR1 Case 17: In addition to the lower air change rate, MERV 15 filters are used. Case 18: In addition to the lower air change rate, MERV 15 filters and an UVGI system are used. Case 19: In addition to the lower air change rate, MERV 15 filters and standalone HEPA system are used.

Table 2: Pressure differentials (Pa) for the six different rooms

Case	Descriptions	Pressure differentials (Pa)																	
		PE1 (Positive)			PE2 (Positive)				AII1 (Negative)				AII2 (Negative)			OR1(Positive)			OR2 (Positive)	
		ΔP_{TR}	ΔP_{NB1}	ΔP_{C}	ΔP_{TR}	ΔP_{AII1}	ΔP_{A}	ΔP_{C}	ΔP_{TR}	ΔP_{AII2}	ΔP_{A}	ΔP_{C}	ΔP_{TR}	ΔP_{NB5}	ΔP_{C}	ΔP_{SC1}	ΔP_{SC2}	ΔP_{OR2}	ΔP_{SC1}	ΔP_{SC2}
1	Baseline	3.67	3.91	4.33	3.74	14.34	1.19	4.40	0.56	-0.85	-3.93	-9.95	0.99	-8.63	-9.10	3.74	1.94	-1.21	4.95	3.16
2	Fixed flow differentials	2.67	1.78	1.99	2.42	4.93	0.02	1.39	1.33	-0.04	-1.00	-3.54	1.41	-3.32	-3.50	1.64	0.01	-1.62	3.27	1.63
3	Door to toilet room open	0.00	3.05	3.43	0.00	13.32	0.59	3.26	0.00	-1.01	-4.01	-10.08	0.00	-8.79	-9.27	3.74	1.94	-1.21	4.96	3.15
4	Door to corridor open	2.03	0.02	0.01	3.56	13.96	3.92	3.92	0.83	-0.03	-7.78	-7.78	2.35	-0.34	-0.01	0.01	-0.24	-3.91	0.01	0.17
5	Increased wall leakage	2.00	1.47	2.52	1.22	6.53	0.04	1.05	-0.00	1.44	-1.72	-4.59	0.16	-3.86	-5.42	1.02	-0.23	-2.77	2.42	0.88
6	Door to anteroom open	3.62	3.92	4.36	3.29	13.32	0.00	3.06	0.87	-0.03	0.00	-8.57	0.92	-8.16	-8.59	3.74	1.94	-1.21	4.96	3.15
Impact of wind																				
7	180°, 1 m/s	3.55	4.16	4.67	3.69	14.58	1.38	4.87	0.57	-0.79	-3.82	-9.70	0.99	-8.57	-8.91	4.13	2.74	-0.65	4.77	3.39
8	270°, 1 m/s	3.55	4.15	4.64	3.70	14.55	1.39	4.89	0.57	-0.79	-3.80	-9.65	0.99	-8.59	-8.86	4.11	2.77	-0.64	4.75	3.41
9	180°, 10 m/s	3.74	3.27	3.51	3.81	13.88	0.73	3.25	0.55	-1.00	-4.22	-10.61	1.02	-8.95	-9.61	3.34	0.00	-2.55	5.89	2.55
10	270°, 10 m/s	3.74	2.49	1.25	5.26	13.11	2.62	7.75	0.82	-0.52	-1.87	-5.33	1.12	-8.12	-4.81	1.37	1.92	-2.20	3.57	4.12

Note that subscripts TR, NB, C, PE, AII, A, SC and OR represent toilet room, normal bedroom, corridor, protective environment room, airborne infection isolation room, anteroom, sterile corridor and operating room, respectively. Details can be found in Figure 1.The terms Positive and Negative in parentheses for each room corresponds to the intended pressure relative to adjacent spaces.

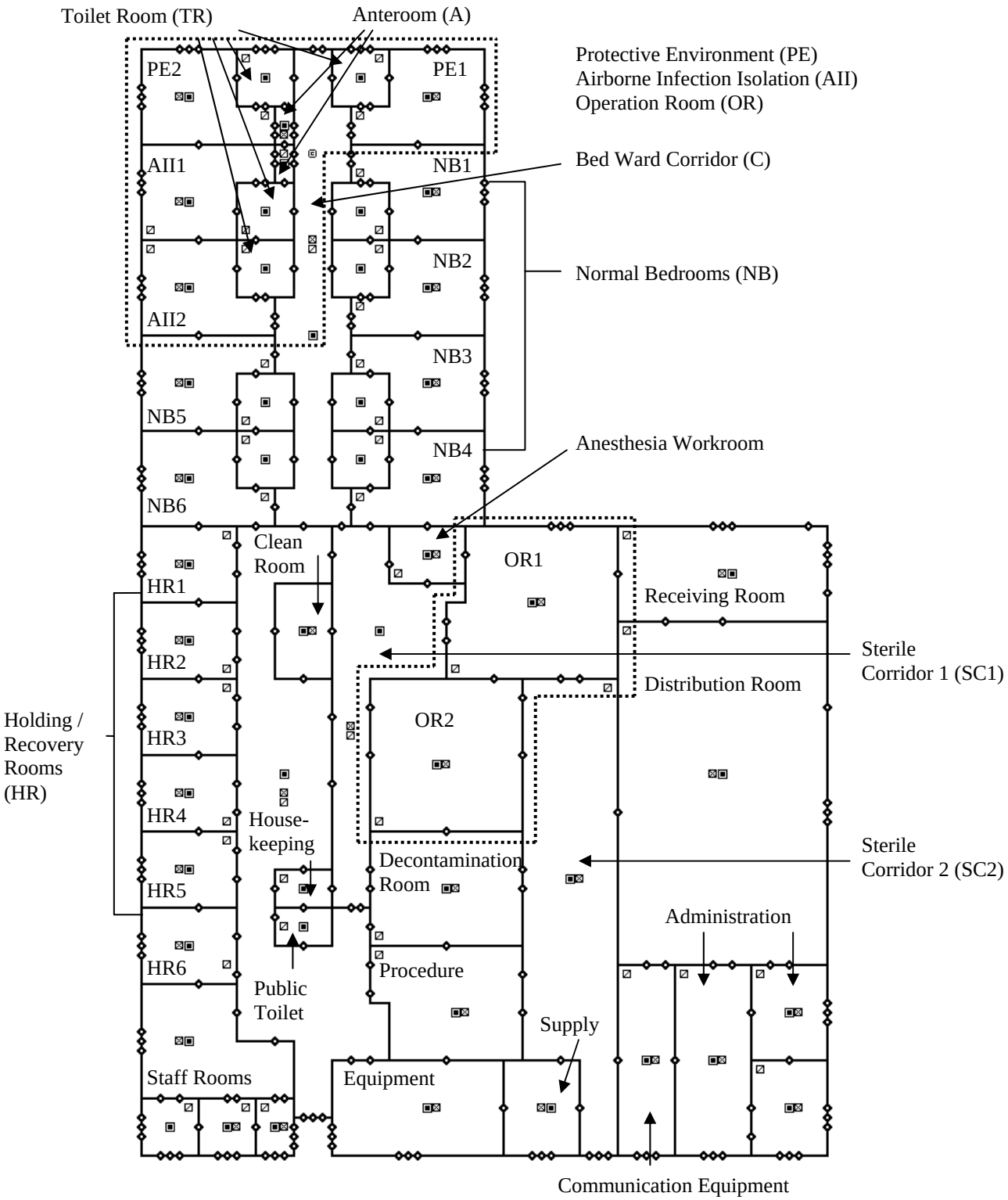

Figure 1: Baseline CONTAM model – Main floor

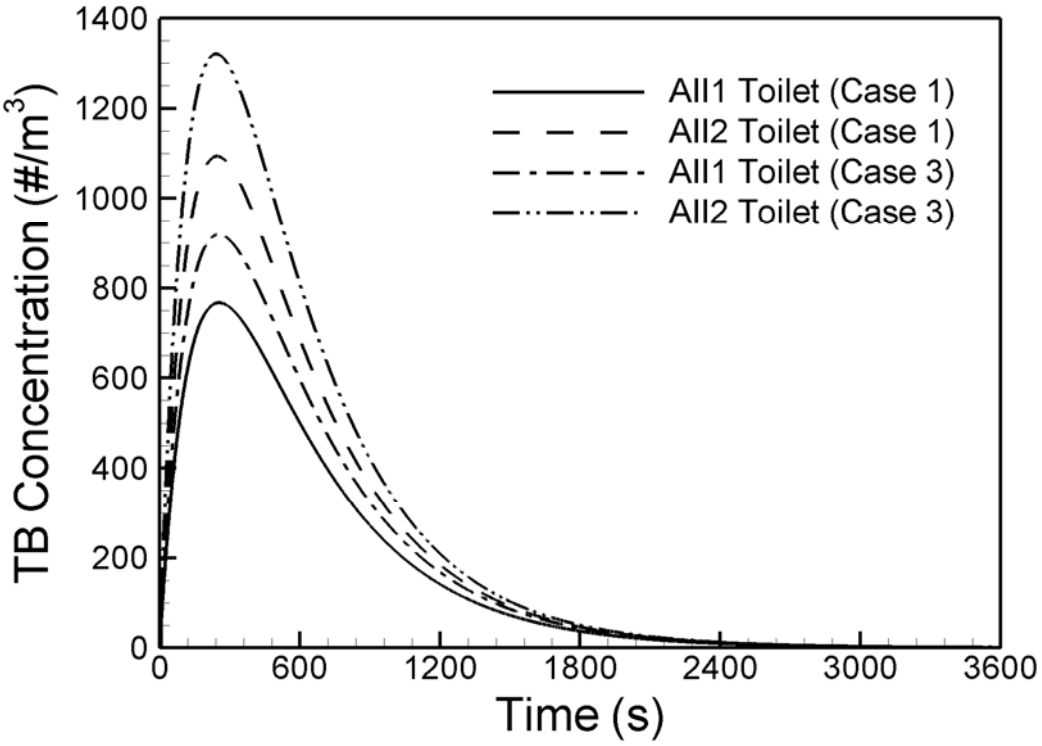

Fig. 2. The effect of toilet door opening on TB-like particle concentration in AII toilet rooms: Cases 1 and 3 correspond to the toilet door being closed (baseline model) and opened, respectively.

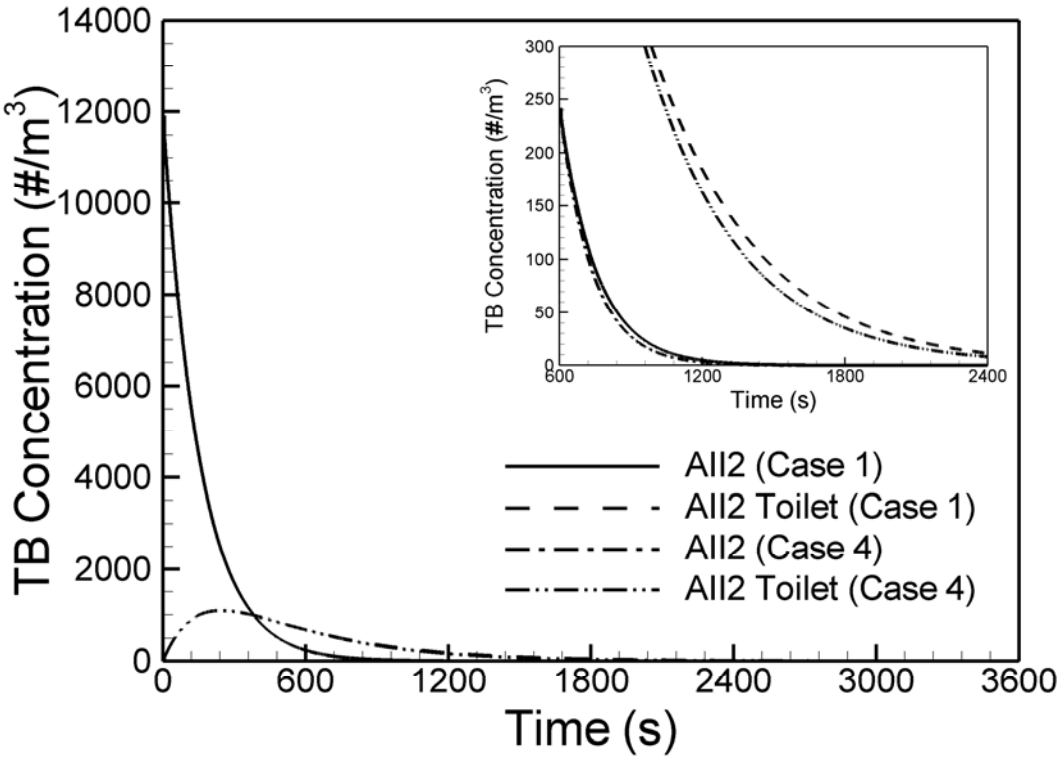

Fig. 3. The effect of the door opening to the corridor on TB concentration in AII suite 2: Cases 1 and 4 correspond to the anteroom door to the corridor in AII suite 2 being closed (baseline model) and opened, respectively.

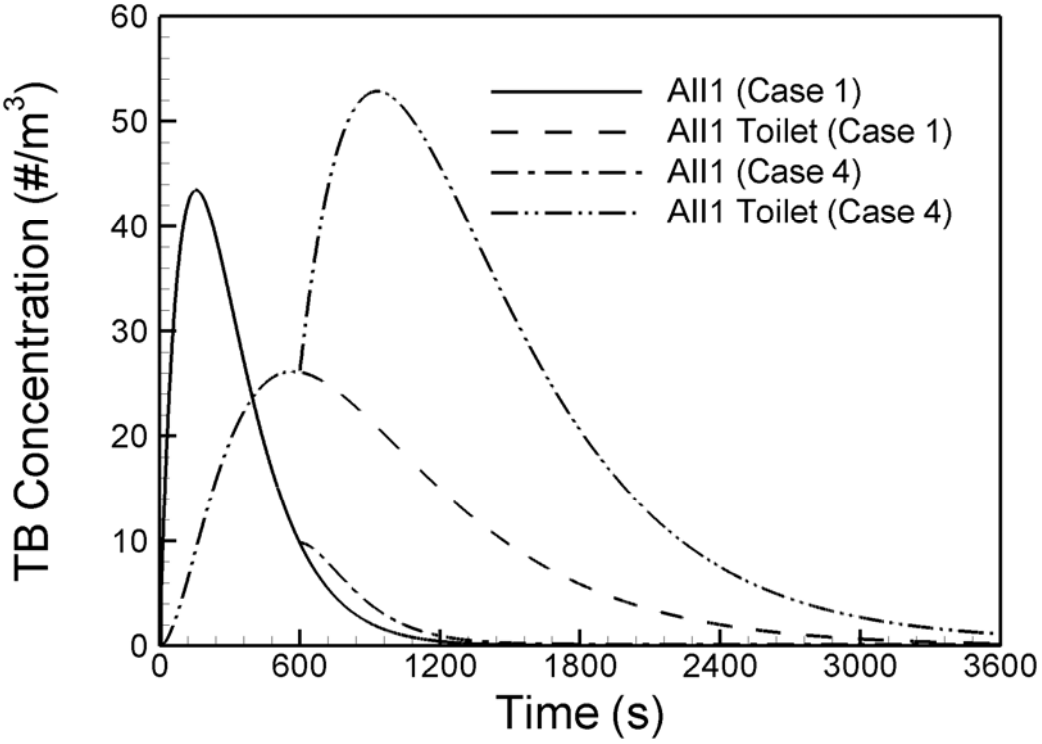

Fig. 4. The effect of door opening to corridor on TB concentration in AII suite 1: Cases 1 and 4 corresponds to the anteroom door to the corridor in AII suite 1 being closed (baseline model) and opened, respectively.

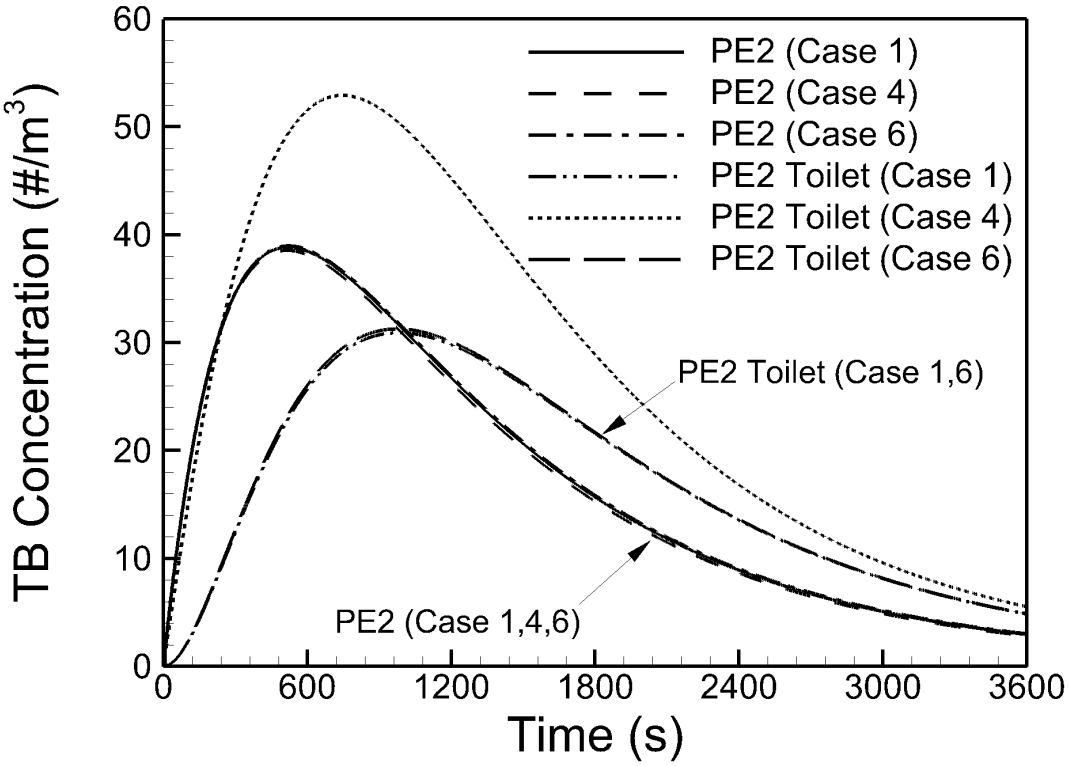

Fig. 5. The effect of anteroom on TB concentration in PE suite 2: Cases 1, 4 and 6 correspond to the anteroom door in PE suite 2 being closed (baseline model), opened to the corridor, and opened to the PE room, respectively.

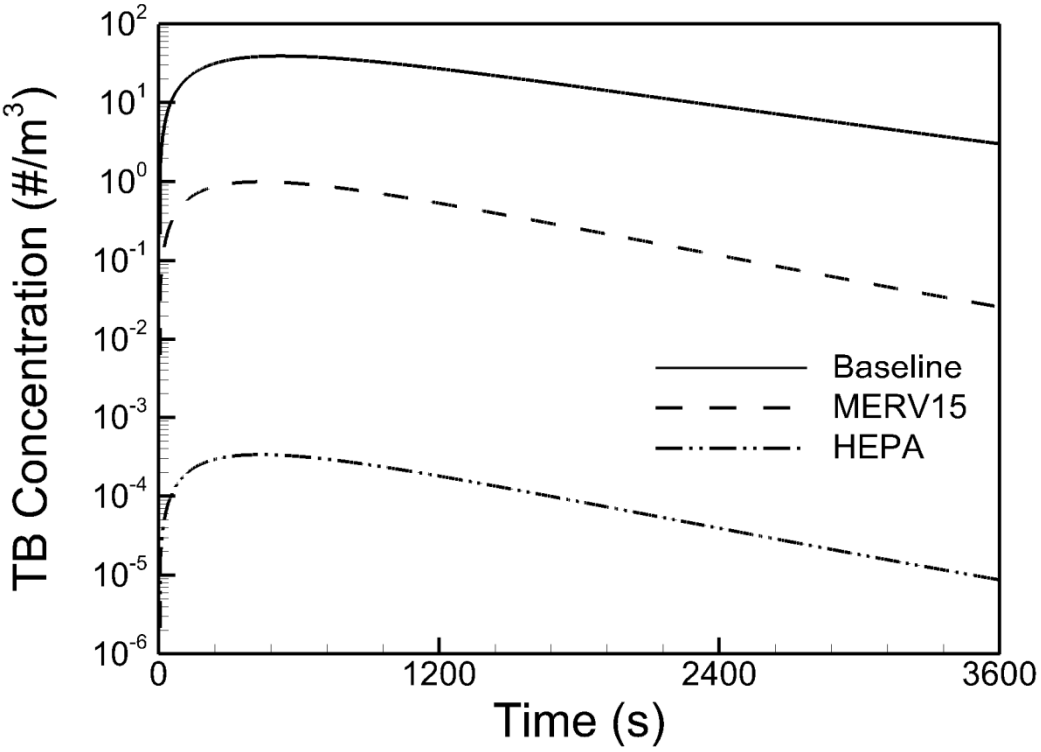

Fig. 6. The effect of air cleaning strategies on TB concentration in PE1.

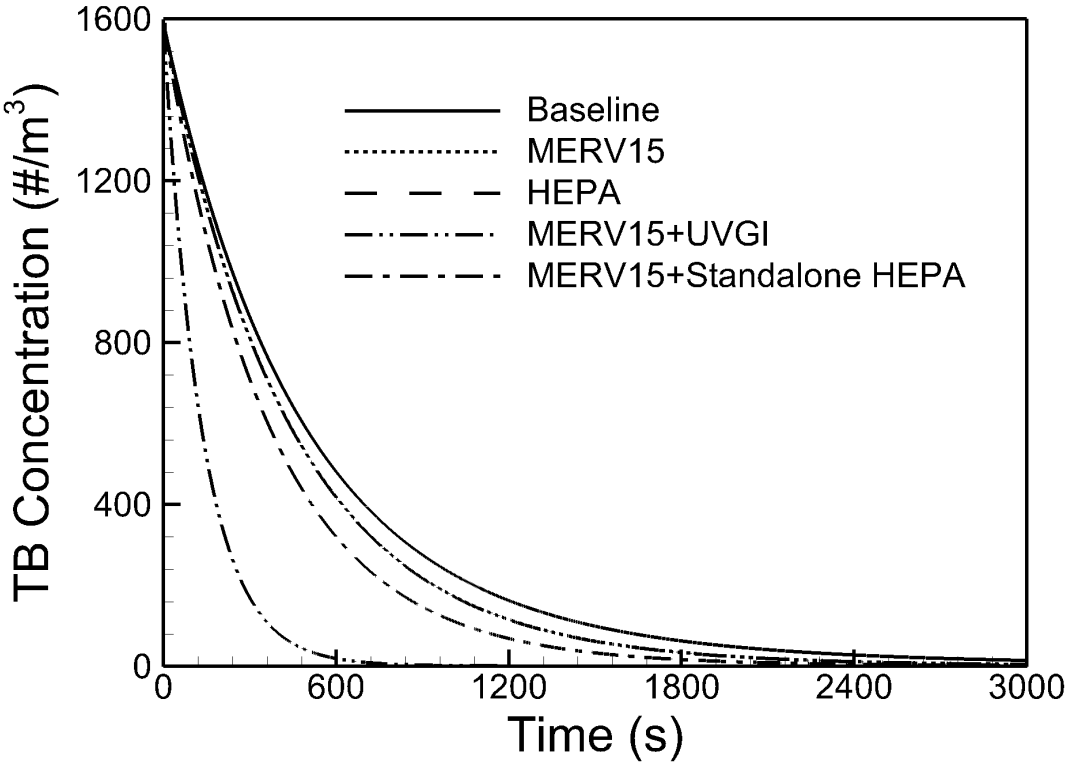

Fig. 7. The effect of air cleaning strategies on TB concentration in the distribution room (DR).

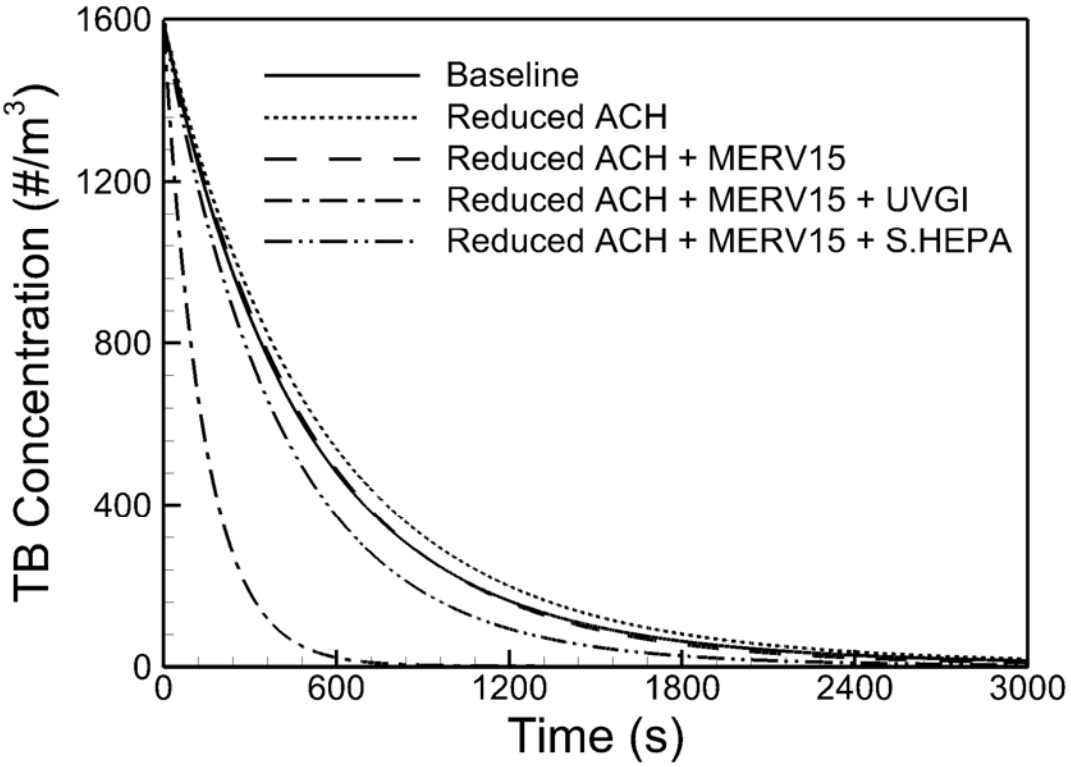

Fig. 8. The effect of air cleaning strategies with a reduced air change rate on TB concentration in the distribution room (DR).

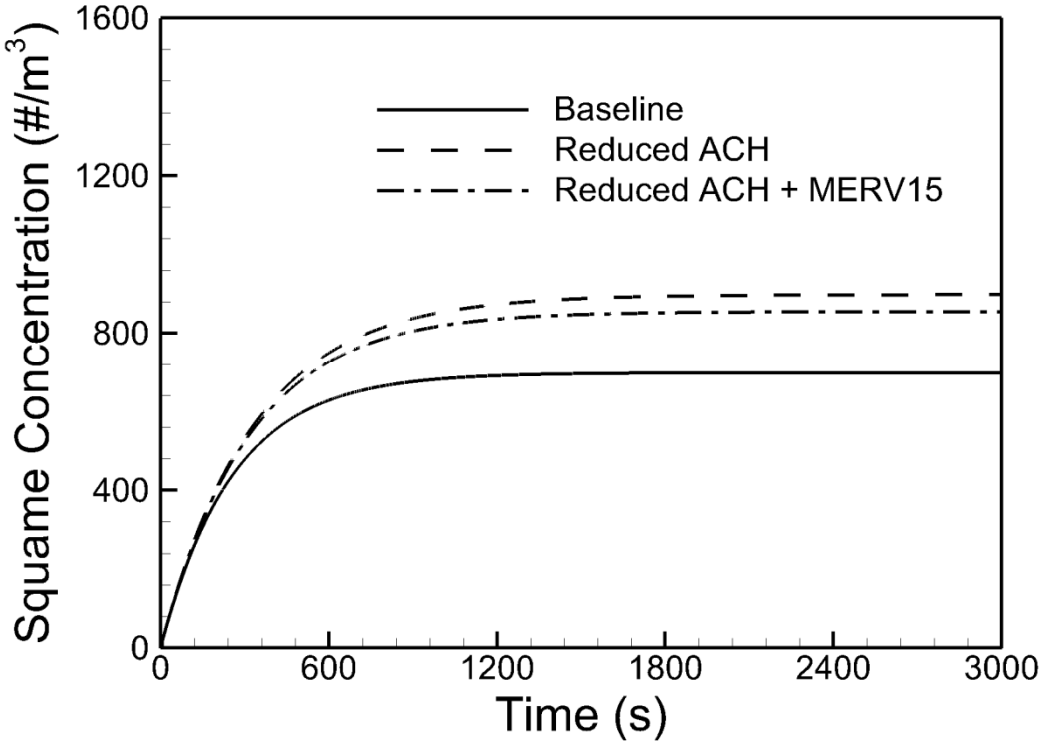

Fig. 9. The effect of air cleaning strategies with a reduced air change rate on squame concentration in OR1.