Improved Ventilation System for

Removal of Airborne Contamination in Airborne Infectious Isolation Rooms

BY JINKYUN CHO, PH.D., ASSOCIATE MEMBER ASHRAE; KYUNGHUN WOO; BYUNGSEON S. KIM, PH.D., MEMBER ASHRAE

The study discussed in this article evaluated the ventilation performance of three strategies for HVAC control for airborne infectious diseases induced by contaminated exhaled air from patients in an airborne infectious isolation room (AIIR). This article examines airflow path and airborne pollutant distribution by computational fluid dynamics modeling and field measurement. In hospitals, the risk of airborne virus diffusion mainly depends on airflow behavior and changes in direction caused by supply air and exhaust air locations. An improved isolation room ventilation strategy has been developed, and is found to be the most efficient in removing contaminants based on observations and simulation results from three ventilation systems.

Introduction

Airborne transmission is one of the main spread routes for a number of infectious diseases such as smallpox and tuberculosis.[1] More than 8,000 reported cases of Severe Acute Respiratory Syndrome (SARS) resulted in 774 deaths and led to a wave of research and standardization of medical facilities with respect to airborne diseases. 36 patients died and 186 people were infected during the outbreak of Middle East Respiratory Syndrome (MERS) in South Korea in May 2015.[2] Outbreaks of such coronaviruses (airborne diseases[3]) in hospitals elevates the risk of infection from patients to health-care workers (HCWs) and other patients. Mainly because of poor ventilation and ineffective disinfection in one hospital, MERS viruses began to spread rapidly to patients, visitors, and even to HCWs.[4] The plan of an AIIR with negative pressure includes a complex process of decisions.

Jinkyun Cho, Ph.D, is senior research engineer at KCL (Korea Conformity Laboratories), Seoul, South Korea. Kyunghun Woo is senior researcher at Samsung C&T Corporation, Seongnam, South Korea. Byungseon S. Kim, Ph.D., is professor at Yonsei University, Seoul, South Korea.

The specifications of mechanical ventilation system, location, layout, interior finishing, and AIIR facilities are critical to the design concepts.[5] Because of exhaust air (EA) and supply air (SA) locations, the risk of virus dispersal at the hospital is influenced by changes in movement and direction of airflow.[6,7]

TABLE 1 Design standards for AIIR to prevent airborne contamination.[11]

	ORGANIZATION	AIR CHANGE RATE (ACH)		PRESSURE DIFFERENTIAL	RECIRCULATION	ANTEROOM
USA	Centers for Disease Control and Prevention	Existing	New/Remodeling	More than 2.5 Pa	Yes (w/HEPA Filter)	Recommend
		More than 6	More than 12			
Canada	Public Health Agency of Canada	Existing	New/Remodeling	–	Yes (w/HEPA Filter)	Recommend
		More than 6	More than 9			
UK	Department of Health		More than 10	More than 5 Pa	No	Recommend
Norway	Folkenhelseinstitutt		More than 12	More than 5 Pa	No	Mandatory
Australia	Department of Health And Human Services	Mandatory	Recommend	More than 15 Pa	No	Mandatory
		More than 12	More than 15			
Hong Kong	Infection Control Committee Department of Health	Existing	New/Remodeling	More than 2.5 Pa	Yes (w/HEPA Filter)	–
		More than 6	More than 12			
South Korea	Centers for Disease Control and Prevention	Mandatory	Recommend	More than 2.5 Pa	Yes (w/HEPA Filter)	Mandatory
		More than 6	More than 12			

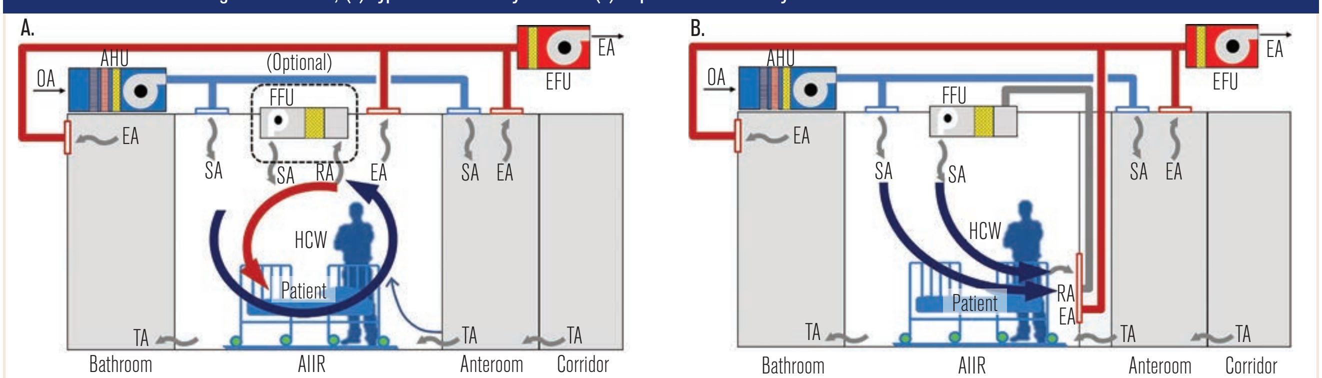
Negative Pressure AIIR Design

As shown in *Table 1*, a negative pressure AIIR design requirement varies from country to country. AIIRs are required to be designed the single-pass approach to bring clean air from the clean zone to the contaminated zone. According to ASHRAE/ASHE Standard 170-2017, *Ventilation of Health Care Facilities*,[8] the pressure difference required to maintain negative pressure is minimum 2.5 Pa. The actual negative pressure level will depend on several factors: differences in the SA and EA volume; airflow paths; and airflow openings and physical configuration of the acute care patient room. To maintain negative pressure in a room, the EA volume needs to be 10% larger than the SA volume. For a room with low airtightness, the HVAC system may not be able to provide the necessary EA/SA airflow differentials.[9] AIIRs in existing health-care facilities needs to achieve at least 6 air changes per hour (ACH) in order to reduce the concentration of pollutants.[10]

The problem of AIIR ventilation systems can include air mixing and inappropriate directional airflow pattern. Ideally, the clean SA should be introduced near HCWs and then, EA should be removed near the patients.[12] The typical AIIR ventilation strategy employs a ceiling SA and ceiling EA system and/or optional air recirculation unit with HEPA filter such as a fan filter unit (FFU).

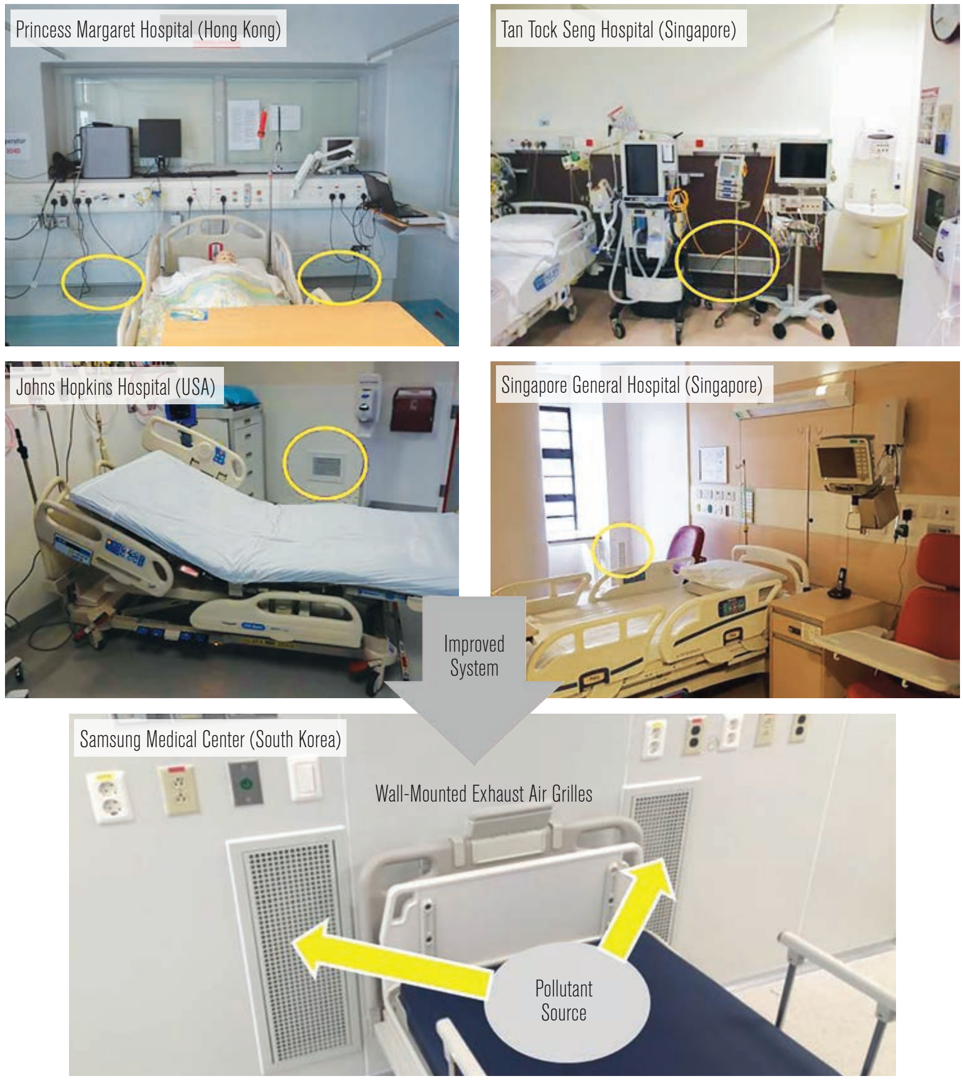
As shown in *Figure 1a*, this ventilation strategy may not efficiently reduce the pollutant concentrations of an infectious source at specific locations due to air mixing in the AIIR. In short, SA is flowed in near staff, but EA is not captured near the patient. There will be an expected high risk of infection from patients to HCWs caused by air mixing in an AIIR. An improved ventilation system in *Figure 1b* as the best arrangement is to have EA grilles on the wall near the floor at the head of the bed, and to have SA diffusers at the ceiling above the foot of the bed. The bottom of the EA grilles should be located about 150 mm above the floor. This ventilation strategy has been

FIGURE 1 Ventilation strategies of the AIIR; (a) typical ventilation system and (b) improved ventilation system.



adopted in some hospitals, but the area in front of the EA grilles is often not kept clear of obstructions such as supply carts and furniture. Because the location of the SA and EA is very important, two wall-mounted EA grilles coupling with a FFU was developed for effective removal of airborne contamination. (*Figure 2*) The overall goal of this study is to find an improved ventilation system based on contaminant concentrations that are the modeled and measured parameter and best design practices should be followed.

FIGURE 2 Determining the better location of EA grilles for AIIR ventilation system.



Numerical Simulation for AIIR Ventilation Strategies

CFD Setups in Numerical Modeling

To investigate the dynamics of the ventilation flow and the airborne contamination in the conditions of a patient who was coughing and breathing was performed on the three CFD models. The AIIR in *Figure 3* shows the locations of the HCWs, patient, door to the bathroom, door to the anteroom, and SA and EA openings for the various cases analyzed in this study. The room has roughly 16 m^2 floor space and 2.6 m ceiling height, with a drop ceiling in part of the room. The sensible heat load due to four occupants (patient and three HCWs) was assumed to be 248 W, whereas the sensible heat load due to the lighting was assumed to be 11.9 W/m^2. The room has an east-facing window with a solar heat gain of 30 W/m^2. All other exterior walls of the room are assumed to be adiabatic. Thus, the total sensible load in the AIIR is assumed to 56.8 W/m^2. The total SA volume and the temperature were specified at 500 m^3/h (12 ACH5) and 16.4°C, respectively. The two square diffusers placed on the drop ceiling are designed to SA 250 m^3/h. The EA flow rate from the room was designed to maintain 400 m^3/h, whereas the bathroom EA flow rate was designed 200 m^3/h. Thus, the total EA flow rate was assumed to be 600 m^3/h with a deficit of 100 m^3/h, which was supplied through the leakage under the main door from the anteroom.

The AIIR was assumed to control under negative pressure and all doors were closed. We first obtained the steady-state solutions for the airflow field, and then tracer gas was continuously released into the AIIR through the source manikin's mouth in bed at a mass fraction of 0.0413, with an upward exhalation velocity of 0.955 m/s. The height of source location (mouth of patient) is 0.9 m above the floor. Boundary conditions and geometries are summarized in *Table 2*. The possible flow paths of airborne contaminants are analyzed

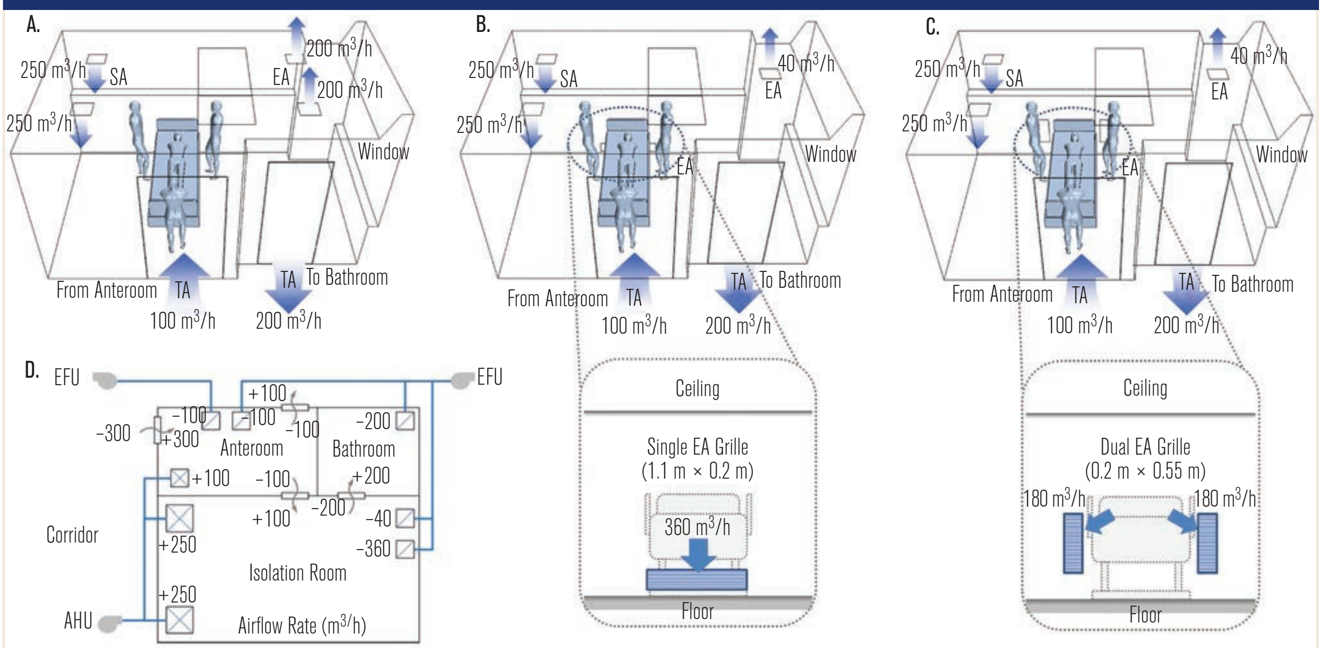
TABLE 2 Boundary conditions with default air change rates.

Supply in AIIR	Default Supply Velocity V_s= 0.772 m/s (500 m^3/h), T=16.4°C
Transfer from Anteroom	V_s= 0.411 m/s (100 m^3/h), T=26.0°C
Transfer to Bathroom	V_s= 0.902 m/s (200 m^3/h), T=26.0°C
Prone Manikins	Uniform Heat Flux 62 W, No Slip Boundary, Standard Wall Function
Mouth of Source Manikin in AIIR	Exhalation Velocity 0.955 m/s, T=30°C, Mass Fraction of Gas (SF_6) is 0.04 (i.e., Gas [SF_6] Release Rate is 0.54 m^3/h)
Walls and Beds	2 and 1 W/m^2 at Ceiling/Floor, No Slip Boundary, Standard Wall Function

TABLE 3 Boundary conditions of EA for ventilation cases.

	EXHAUST AIR (DEFAULT EXTRACT VELOCITY V_e)			
	Total	Ceiling	Wall-Mount (Under Bed)	Wall-Mount (Behind Bed)
Case 1 (Base)	400 m^3/h	400 m^3/h V_e= 0.617 m/s (0.3 m × 0.3 m) 2 EA	–	–
Case 2		40 m^3/h V_e= 0.123 m/s (0.3 m × 0.3 m) 1 EA	360 m^3/h V_e= 0.455 m/s (1.1 m × 0.2 m) 1 EA	–
Case 3		40 m^3/h V_e= 0.123 m/s (0.3 m × 0.3 m) 1 EA	–	360 m^3/h V_e= 0.455 m/s (0.2 m × 0.55 m) 2 EA

FIGURE 3 CFD modeling for ventilation strategies; (a) ventilation Case 1, (b) ventilation Case 2, (c) ventilation Case 3 and (d) airflow diagram of the AIIR and surroundings.



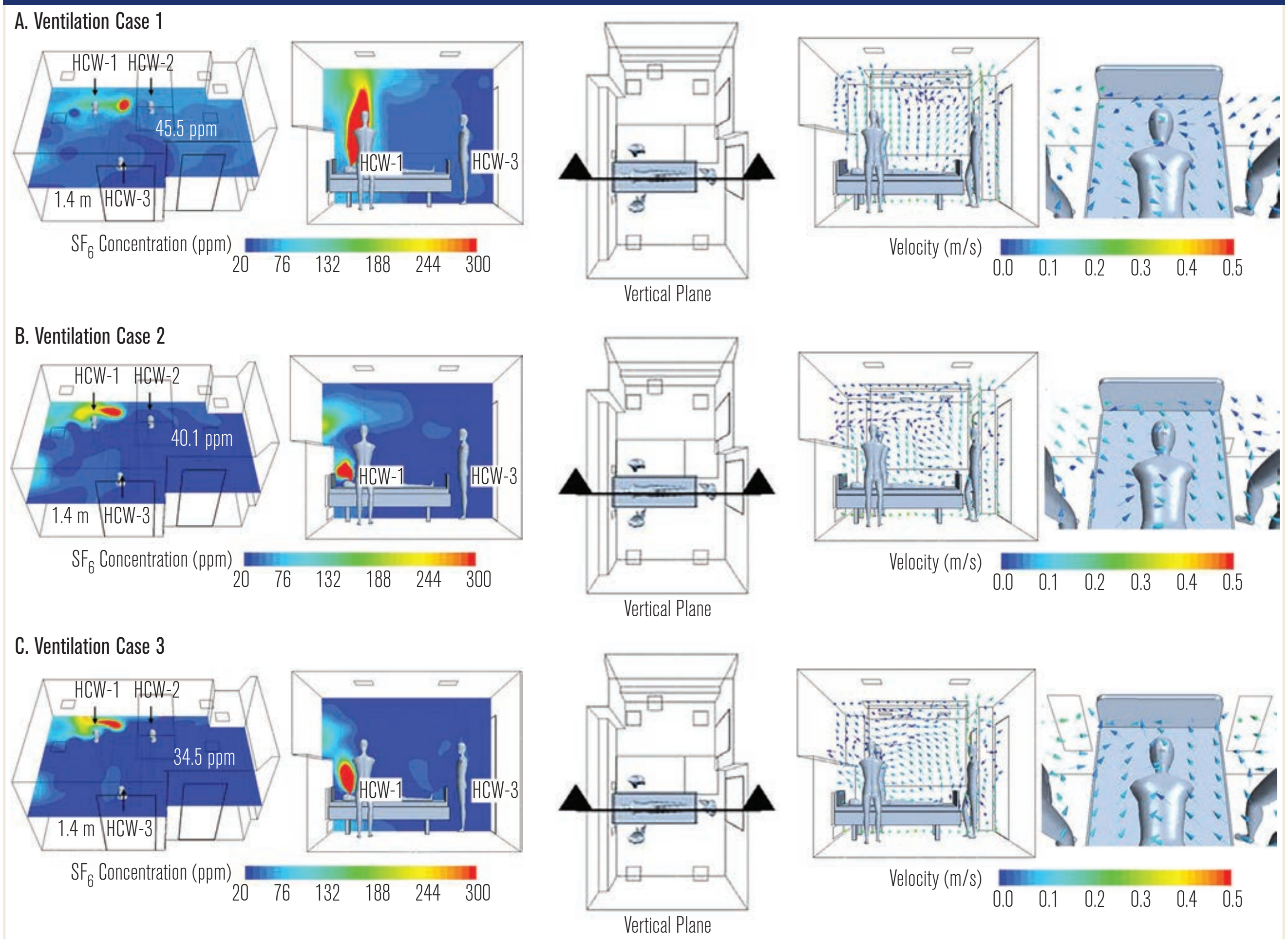
by tracing the airflow pathways emitted from the face of patient. This analysis focuses upon low-momentum pathogen releases (i.e., does not focus on high momentum releases such as full-volume coughing) and assumes most of the airborne pathogens emitted from the face of patient would follow the flow path of the air, neglecting any settling and deposition of these particles on the surfaces. A total of three cases analyzed for various locations of EA grilles are described below and in *Table 3*.

- Case 1: Ceiling SA diffusers over left side of patient's head and ceiling EA grilles near the toilet door (*Figure 3a*).
- Case 2: Ceiling SA diffusers over left side of patient's head and the ceiling exhaust replaced with the low-wall horizontal EA grille placed under the patient's bed at 0.2 m above the floor (*Figure 3b*).
- Case 3: Ceiling SA diffusers over left side of patient's head and the ceiling exhaust replaced by two wall mounted EA grilles placed behind the patient's head at 0.2 m above the floor (*Figure 3c*).

Numerical Simulation Results

Computational results for each case are presented in the form of color contour plots showing pollution distribution and vector plot. They show the probable path of contamination released from the patient and the airflow

FIGURE 4 Simulation results of concentration profile of SF_6 and velocity vector plot; (a) Ventilation Case 1, (b) Ventilation Case 2 and (c) Ventilation Case 3.



distribution in AIIR. *Figure 4* shows concentration distribution patterns at a 1.4 m horizontal plane, representing the respiration level of the HCWs during patient treatment. The concentration of pollutants is reduced as they move away from the patient. The stagnation of air was observed in some regions with the high concentration of pollutants. It was observed that there is air short-circuiting between the SA diffusers and the EA grilles from the vector plot of air velocity. In the AIIR, the CFD simulation used to predict pollutant distribution profiles and airflow pattern was well analyzed. The absolute concentration value of pollutant has no significance in this research. Rather, it is the relative concentration profile between one ventilation system and the other that is very important. *Table 4* shows the exposure level of pollutant to the HCWs. Ventilation Case 1 has high concentration values ranging between 33.1 and 72.7 ppm. The lowest concentration is observed around HCW-3, while the highest concentration is observed at HCW-1. While treating the patient, the HCW will likely be standing at 1.4 m with the higher exposure level of pollutants.[14]

It indicates that Case 1 is poor for removing pollutants from the AIIR. Compared with Ventilation Case 1, Ventilation Case 2 and Case 3 have lower concentration values, ranging between 25.1 and 34.4 ppm, and between 21.2 and 24.4 ppm, respectively. *Table 5* shows the percentage difference of predicted concentration between the ventilation Case 1, Case 2 and Case 3. When the HCWs were treating the patient, there was a large difference in the pollutant exposure level. At 1.4 m the average value of pollutant concentration for Case 2 was 11.9% lower than in Case 1. Similarly, Case 3 was more effective in removing contaminant in the AIIR compared to Case 1 and Case 2 with 24.2% and 14.0%, respectively. For the average concentration of whole room, Case 2 was lower than Case 1 with 22.7%. Exposure level of Case 3, 34.8 ppm, was lower compared to Case 1 (48.4 ppm) and Case 2 (37.4 ppm). Ventilation Case 3, which was the best of three cases to remove pollutant from AIIR, bound to improve efficiency with 28.1% of Case 1 and 7.0% of Case 2. A clean air moves from the HCWs to the patient resulted in the improved airflow pattern in health-care facilities. The use of a single-pass setup is expected to lower the risk of infection from patients to HCWs. These results indicated that placement of EA grilles directly behind the patient's head can potentially provide a ready flow path for airborne contamination to exit the AIIR without significant recirculation and entrainment back into the SA stream. A combination of locations and types of SA diffusers, and locations of room EA and SA flow rates can affect the airflow patterns in the AIIR, which are quite complex and specific to a particular design configuration. The airflow profile at the patient's bed is less than 0.25 m/s within the recommended threshold air velocity value.

TABLE 4 The pollutant's exposure level of the HCWs.

	MEAN SF_6 CONCENTRATION (PPM)		
	VENTILATION CASE 1	VENTILATION CASE 2	VENTILATION CASE 3
HCW-1 (1.4 m)	72.7	34.4	24.4
HCW-2 (1.4 m)	40.0	27.6	21.2
HCW-3 (1.4 m)	33.1	25.1	21.3
Average of 1.4 m level	45.5	40.1	34.5
Average of Room	48.4	37.4	34.8

TABLE 5 The pollutant concentration percentage difference of three ventilation cases.

	SF_6 CONCENTRATION PERCENTAGE DIFFERENCE					
	VENTILATION CASE 1 (C_{V1})		VENTILATION CASE 2 (C_{V2})		VENTILATION CASE 3 (C_{V3})	
Percentage Difference	Base	$(C_{v1}-C_{v2})/C_{v2}$	$(C_{v2}-C_{v1})/C_{v1}$	Base	$(C_{v3}-C_{v1})/C_{v1}$	$(C_{v3}-C_{v2})/C_{v2}$
HCW-1	0.0	34.4	–52.7	0.0	–66.4	–29.1
HCW-2	0.0	44.9	–31.0	0.0	–47.0	–23.2
HCW-3	0.0	31.9	–24.2	0.0	–35.6	–15.1
Average of 1.4 m Level	0.0	13.5	–11.9	0.0	–24.2	–14.0
Average of Room	0.0	29.4	–22.7	0.0	–28.1	–7.0

Full-Scale Field Measurement

The "S" medical center decided to permit ventilation Case 3 for negative pressure AIIRs according to the results of the preliminary ventilation strategies study. A series of full-scale field measurements were conducted in this hospital, Seoul, Korea in 2016. This research was carried out in a negative pressure AIIR on the second floor of an unoccupied three-story isolation unit extension before the official opening. The new isolation unit had six negative pressure AIIRs and two intensive care units (ICU). The second floor consists of a corridor with four AIIRs. Each floor of the isolation unit has a separate constant air volume (CAV) ventilation system that provides 100% OA. Filtration was achieved using minimum efficiency reporting value (MERV) eight panel filters.[15,16] As shown in *Figure 5a*, the anteroom was maintained at a pressure –2.6 Pa with respect to the corridor when the door between the corridor and anteroom was closed. Likewise, a correctly functioning AIIR was maintained at a pressure –3.8 Pa in respect of the anteroom when the AIIR-anteroom door was closed. Every two AIIRs have their own toilet but use a shared anteroom. Air in the AIIR was exhausted through the bathroom's fan. There were two ceiling SA diffusers and one ceiling EA grille and two low-wall EA grilles placed behind the patient's head at 0.2 m above the floor level.

The unique properties of sulfur hexafluoride (SF_6) have led to its adoption for a number of industrial and scientific applications including tracer gas for studying airflow in ventilation systems. Research on the diffusion of such pathogens as viruses or pollution sources generally assume discharged air from breathing to be the source of the pollution or pathogen and then analyze its diffusion. In these experiments, SF_6 was used as tracer gas. SF_6 injection rate is regulated via a mass flow controller and SF_6 was continuously released from a cylinder as a point emitting tracer gas at 1.09 L/min. The volumetric flow rates were measured by multi-gas sampler and doser and photoacoustic multi-gas monitor. The total air change rate of the AIIR is 12 ACH. *Figure 5* shows the locations of sampling and injection in the AIIR. At a constant rate of tracer gas, SF_6 was injected near a patient's bed at 0.9 m above floor. A tracer gas analyzer continuously measured at six sampling locations for the concentration of SF_6. To evaluate the pollutant exposure level of the HCW, three points (SP-1, SP-2 and SP-3) were located near the bed at 1.4 m from the floor. These measuring points were selected, as HCW will be standing at these points while treating the patient.[14] Two sampling points (SP-4 and SP-5) were located at the two EA grilles to evaluate for removing pollutants in the room. And one sampling point (SP-6) was in the anteroom.

FIGURE 5 (a) Pressure differential between rooms, (b) field test room and measurement instruments and (c) position of sampling points in the AIIR.

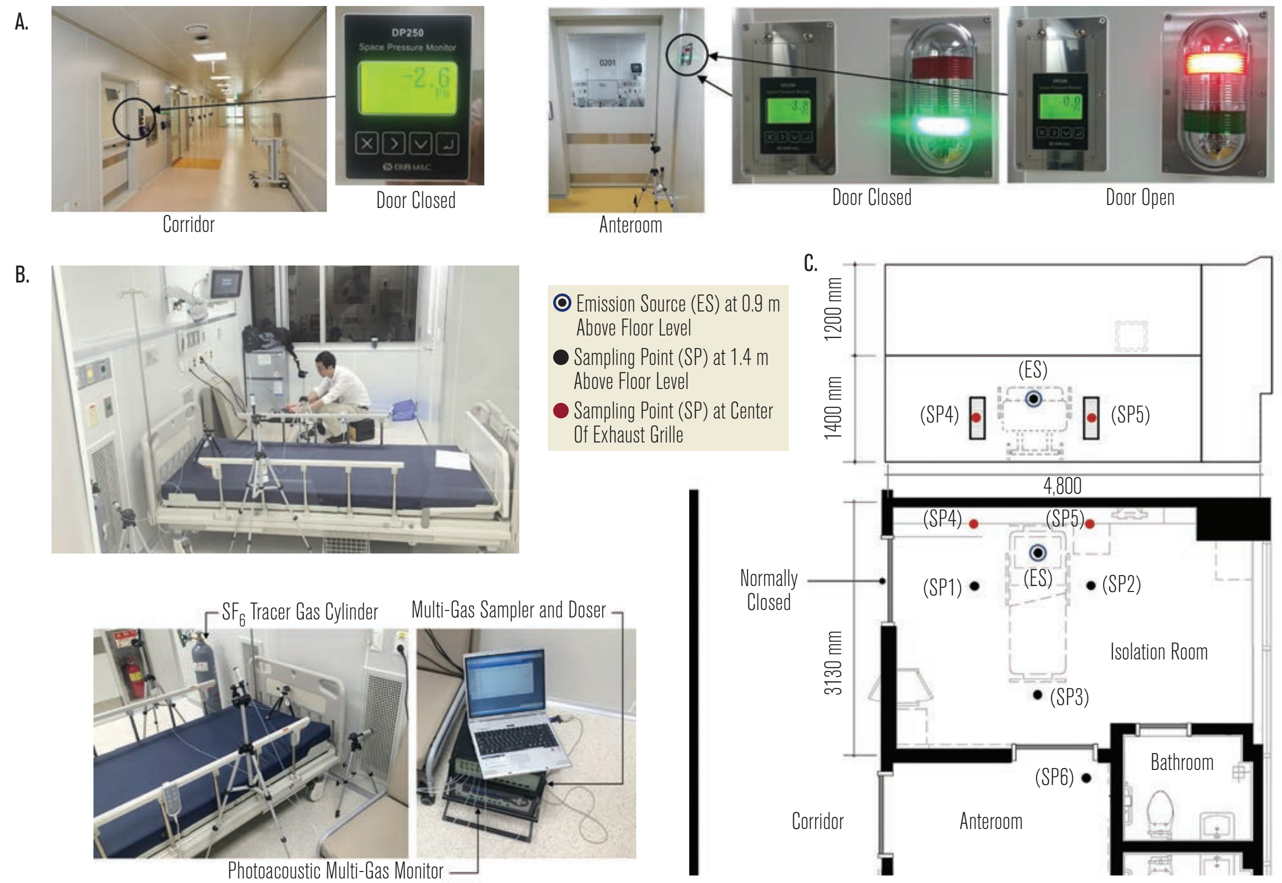
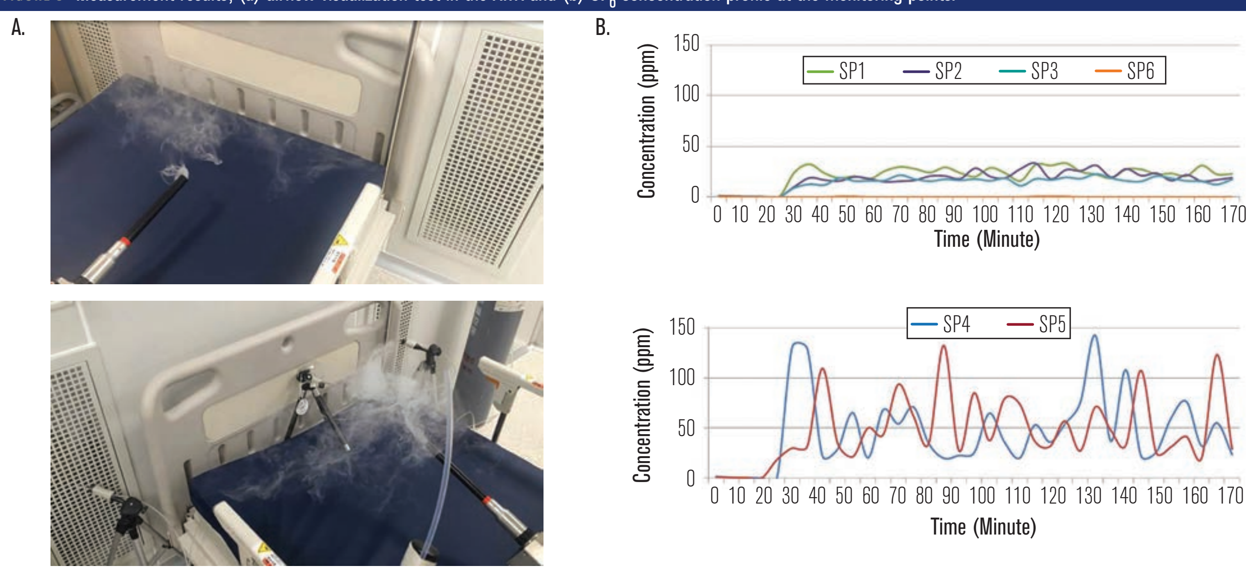


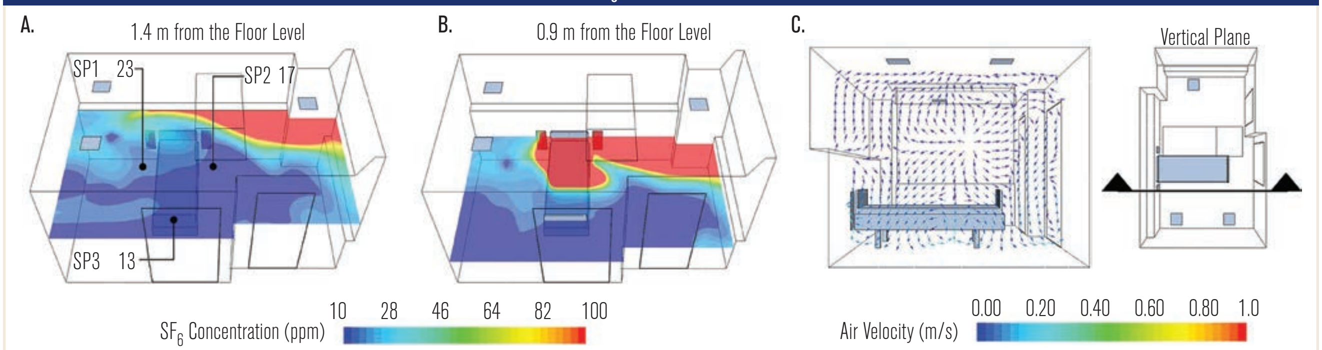
FIGURE 6 Measurement results; (a) airflow visualization test in the AIIR and (b) SF_6 concentration profile at the monitoring points.



Measurement Results

Smoke testing was used to visualize the air movement directions in the AIIR and to evaluate how well pollutants are removed. *Figure 6a* shows the results of a smoke test conducted in a negative pressure AIIR, visualizing airflow by using a portable fog generator. Results showed that the indoor air did not mix or spread inside of the AIIR, but was discharged immediately through two low

FIGURE 7 CFD simulation verification results; (a), (b) concentration profile of SF_6 and (c) velocity vector plot.



wall EA grilles placed behind the patient's head. *Figure 6b* illustrates the SF_6 concentration profiles at the six monitoring points in the AIIR. As SF_6 was injected, the tracer gas concentration increased rapidly at monitoring locations SP-1 through SP-5. It was observed that the concentration trend at each point reached equilibrium after 20 minutes and showed a similar profile. Monitoring location SP-6 shows only trace levels for concentration of SF_6. This means that there was no airflow from the AIIR to the anteroom when the door was closed and the AIIR was under negative pressure. At SP-4 and SP-5, the two EA grilles, the SF_6 concentration continued to maintain at a higher concentration than the other three monitoring locations over the period of measurement. The SF_6 concentration of SP-4 and SP-5, have dynamic range of pollution concentration, also increased at a faster rate as compared to those concentration at the other locations. Average pollution concentration on SP-4 and SP-5 is 46.2 ppm and 47.1 ppm, respectively. This was over 2.2 to 3.3 times higher than on SP-1 (21.5 ppm), SP-2 (17.8 ppm), and SP-3 (14.4 ppm). It is assumed that these average values were so small due to airflow movement caused by the large area of the EA grilles. Assuming maximum values, maximum pollution concentration on SP-4 and SP-5 is respectively 142 ppm and 132 ppm, which are over 4.2 to 5.8 times higher than on SP-1 through SP-3. Consequentially, it was determined that pollutants were removed with high efficacy.

Simulation Verification

For verification of the CFD simulation, the AIIR with ventilation Case 3 (*Figure 3c*) was compared with on-site measurement data. In the modeling of contaminant's migration patterns under steady-state condition, besides specifying the flow conditions across the boundaries, the neighboring rooms' conditions of the source term within the continuum and its boundaries must be defined.[14] Boundary conditions were about the same for the ventilation Case 3 except total heat load and SA temperature. These analyses were carried out for partial load conditions that are more prevailing than the peak design load conditions. Because field measurement was carried out at night and there was almost no difference between indoor and OA temperature, the windows and exterior walls of the room were assumed to be adiabatic. The total sensible heat load was assumed to be 11.95 W/m^2 in consideration of artificial lighting only. The OA was supplied to the room at 24.6°C. The release source was simulated at 1.09 L/min., as a point discharging SF_6. *Figure 7a* shows the horizontal concentration distribution pattern of 1.4 m from the floor representing the HCWs' respiration level when attending to the patient. The dispersion of contaminants is not symmetrical, which is influenced by the indoor airflow pattern. As shown in *Figure 7b*, around the patient's breathing level at 0.9 m from the floor, it is clear that the highest pollutant concentration is found. The concentration of SF_6 is lower as they move away from the patient. *Figure 7c* illustrates the predicted airflow pattern of a vertical section of the AIIR. The air flows toward the patient and is discharged via two EA grilles mounted on the wall and one ceiling EA grille in the room. The patient on the bed is experiencing about 0.10 m/s airflow. This velocity is the recommended value of less than 0.25 m/s.[17] As shown in *Table 6*, the measured concentration correlates well with the predicted concentration at SP-1, SP-2 and SP-3 that are the breathing level of the HCW. The percentage difference between the simulation and measurement results ranged between –9.7 and 7.0. This model is reasonably accurate to evaluate the profile of pollutant in the AIIR. Since the simulation results give concentration ranges similar to those of the measurements, we consider the simulation method to be primarily validated. Therefore, we used the same simulation method to carry out additional analysis. In the validation work, it should be noted that the multi-component gas type and emission rate of the source is 1.09 L/min. Before validation of the prediction results against the measurement results, the model was already modified, representing the ventilation cases.

Conclusions

This research evaluated the performance of ventilation strategies and the HVAC controls of airborne contamination from patients in AIIRs of hospitals. This study has conducted to increase the understanding of the improved ventilation system, including both numerical simulation and full-scale experimental work. It demonstrates that the airflow paths, induced SA flow paths, and EA grille placement can be coordinated to establish effective contaminant control. Locations of the SA and EA openings are the most important elements that directly affect the pollutants dispersion in the room. Thus, a careful evaluation of the HVAC configuration can help in gaining insight and optimizing the flow path of air to obtain the desired combination of occupant thermal comfort and the best possible hygienic conditions in the AIIR. A combination of locations, EA/SA diffuser types and EA/SA flow rates can affect the airflow patterns in the AIIR, which are very complex and specific to a particular design configuration. In this research, AIIR ventilation strategies for reducing the exposure level of pollutants have been developed. They are as follows:

- Arrange EA grilles and SA diffusers to allow clean SA to move from the clean area (HCW) to the contaminated area (patient), and exhausted from the AIIR.
- There was large difference in the pollutant exposure level to the HCWs, when attending to the patient. At 1.4 m location average value of pollutant concentration, Case 2 (ceiling SA and low wall EA under the patient's bed at 0.2 m above the floor) was 11.9% lower than in Case 1 (ceiling SA and ceiling EA). Similarly, Case 3 (ceiling SA and the two wall mounted EA behind the patient's head) was more effective for removing pollutants in the room than Case 1 and Case 2 with 24.2% and 14.0%, respectively.

The chosen ventilation system has an influence on the pollutant distribution and airflow pattern in the AIIR. Ventilation Case 3 is the improved system to reduce the pollutant's exposure level of the HCW from the patient.

TABLE 6 Corroboration of simulation and measurement results.

Sample Point	Mean SF_6 Concentration (ppm)		Percentage Difference $(C_S - C_M)/C_M$
	CFD Simulation (C_S)	Field Measurement (C_M)	
SP-1	23	21.5	7.0
SP-2	17	17.8	–4.7
SP-3	13	14.4	–9.7

These findings are expected to provide important evidence that can aid in the development of design strategy for effective removal of airborne contamination in AIIRs.

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