Design Method to Prevent Airborne Infection in an Emergency Department

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Abstract
This study investigated design recommendations to reduce airborne infection risk in an emergency department by using airflow network simulation. The main design concepts include isolating the source of the airborne pathogen and increasing the ventilation rate. A conventional emergency department is selected as a base model, and influenza is selected as the airborne pathogen examined in the study. The Wells–Riley equation is used to model airborne infection risk in a zone. The simulation results indicate that airborne infection risk exists when a patient releases an influenza pathogen in the emergency department with a ventilation rate of 3 ACH according to the Korean building code. The findings reveal that isolating the airborne pathogen source and increasing the ventilation rate are good methods to prevent airborne infection risk. However, the isolation method can increase the infection risk in a zone with an airborne pathogen source. Thus, it is necessary to simultaneously increase the ventilation in a zone with an airborne pathogen source. Additionally, airborne infection risk continuously increases the cumulative exposure time, and it is desirable to increase the ventilation rate required for a zone based on the residing time of a patient releasing airborne pathogens in a target zone.

Keywords: airborne infection; ventilation; isolation room; Wells–Riley equation; emergency department

1. Introduction
Recently, airborne infections in hospitals have emerged as a social problem in South Korea. Patients with respiratory symptoms of an airborne disease can easily visit hospitals. Additionally, medical staff and visitors are often in the same area as such patients, and thus, a cross-infection risk exists (Kowalski 2006).

In developed countries, it is considered that a crucial design factor to prevent airborne infection in a hospital is to increase the ventilation rate from 6 ACH (air change per hour) to 12 ACH (AIA, 1996–97). However, in the case of South Korea, design standards to prevent airborne infection in hospitals are not clearly presented to date in terms of building code requirements.

Various attempts to build new constructions for airborne infection control have been implemented. However, suitable countermeasures for preventing airborne transmission in a conventional emergency room are absent in South Korea. Evidently, the most effective method involves significantly increasing the ventilation rate of the emergency department when the cost is not considered (Nardell, 1991; Zhou, Qi, et al. 2017; Qian, Hua, et al. 2010).

However, in the case of existing buildings or small buildings, it is difficult to change an HVAC (heating, ventilation, and air-conditioning) system in a short time. Specifically, emergency rooms are associated with high risks of spread of airborne infection owing to their open floor plans and lack of adequate facilities (Cheong & Seo, 2016). Previous studies (Li et al., 2007) did not provide strong scientific evidence for infection control. Therefore, it is helpful to provide design guidelines that can be applied in early stages of the design implementation of hospital facilities. Hence, this study presents a case study detailing the performance of airborne infection risk evaluation in a conventional emergency department and verifies the design recommendation.

2. Methods
2.1 Simulation Tools
In this study, CONTAMW ver 3.2 is used to analyze the transmission of airborne pathogens. This program utilizes airflow network, and it can simply analyze airflow patterns and airborne pollutant concentrations in a multi-zone building. Existing studies used CONTAMW to analyze airborne pathogen transmission in hospitals (Noakes, 2008; Park, et al. 2011).
2.2 Wells–Riley Equation

In this study, CONTAMW is used to identify the concentration of airborne pathogens in a specific zone. However, the concentration of airborne pathogens obtained by CONTAMW does not correspond to the probability of airborne infection. Therefore, to analyze the risk of airborne infection in a specific zone, it is necessary to convert the concentration value of the airborne pathogen to the probability of airborne infection. Generally, the Wells–Riley model is used to evaluate the risk of airborne infection (Wells, 1995; Rudnick, 2003; Issarow, 2015; Zhu, 2011, Quan, 2009). Equation 1 presents a general expression of the Wells–Riley model for a well-mixed condition as follows:

\[ P_I = \frac{C}{s} = 1 - e^{-\frac{qt}{q}} \quad \text{...} \quad (1) \]

where
- \( P_I \): airborne infection probability of a susceptible person
- \( C \): number of infection cases
- \( I \): number of infectious individuals
- \( p \): breathing rate of a susceptible individual (m\(^3\)/min)
- \( q \): quantum generation rate by an infectious individual
- \( s \): number of susceptible individuals in the space
- \( t \): duration of exposure

2.3 Target Area

The emergency department is functionally divided into various areas. Therefore, it is necessary to distinguish between the space in which an airborne pathogen is emitted and the space in which infection occurs. It is assumed that a patient with an airborne infection pathogen visiting an emergency department first travels through a triage area located near the entrance. Subsequently, a simple diagnosis is performed in the triage area, which lasts for approximately 30 min. The patient is thereafter moved to the general treatment area or acute treatment area to receive medical treatment. In the study, a situation is selected in which a patient's circulation begins from the entrance and proceeds to a triage/general treatment area.

Fig.1. conceptually illustrates the assumed risk of each area in an emergency department with respect to the transmission of airborne infection. It is assumed that the risk of airborne infection corresponds to the openness of the area and the densities of patients, companions, and medical staff.

Table 2. presents the target spaces analyzed in the study. Specifically, patient medical treatments are performed in the general treatment area, and it is assumed that there is a high possibility of airborne transmission in this area. The triage area is a place where patient urgency is determined. Thus, all patients visit the triage area. Therefore, in the triage area, there is a high latent possibility of cross-infection between the patient and medical staff at all times. The waiting room is the space where the patient's caregiver waits while the patient receives medical treatment. Generally, it is located extremely close to the entrance area (vestibule/lobby) and triage, and thus, airborne pathogens generated from the triage area are easily transferred to this area.

Table 1. Representative Areas in an Emergency Department

| Spaces          | Features | Usage                                      |
|-----------------|----------|--------------------------------------------|
| Triage Area     | Opens to the lobby | Determine severity of patient's condition  |
|                 |          | Perform a simple diagnosis                  |
| General treatment area | Open area | Patients usually receive medical treatment |
| Waiting room    | Separated area | -Waiting area for a caregiver               |

2.4 Major Variables

In this study, methods considered for preventing airborne transmission are as follows:

1. Isolating the source of the airborne pathogen
2. Increasing the ventilation rate in the area

Architecturally, it is possible to divide an open space into partitioned individual spaces. The use of partitions to separate an area is an easy method to prevent airborne pathogen transmission without replacing the HVAC system. Thus, a patient's family or caregiver can wait in the waiting room of an emergency department. Generally, these individuals are not considered to be infected by the airborne disease. Thus, it is necessary to prevent the transmission of the airborne pathogen from other areas of the hospital to this waiting room. The waiting room area is adjacent to the entrance and lobby. Two types of waiting rooms are considered. The first type of waiting room opens to a lobby and a triage area. The second type of waiting room is isolated from the lobby and triage area and opens to the vestibule. In this case, the door between the vestibule and lobby (triake area) is closed.

Increasing the ventilation rate is a classical and certified method of reducing the concentration of airborne pathogens, resulting in reduced airborne infection risk. The building code guidelines in South Korea do not specify the detailed design guidelines for HVAC systems in an emergency department. The
existing building code only necessitates a ventilation rate of 36 m$^3$/person·hour in large hospitals with floor areas exceeding 2000 m$^2$. This corresponds to approximately 2.4 ACH when the minimum floor area required for a patient is considered (Sung, 2015). Table 2. lists the air change rates in an emergency department as specified by previous studies (Cho et al., 2016; Sohn et al., 2014; Park & Kim, 2012; ASHRAE). The baseline for the ventilation rate in an emergency department area is assumed to be 3 ACH. The following two variables are considered to identify the effect of increased ventilation rate on the dispersion of an airborne pathogen in an emergency department: ventilation rates of 6 ACH and 12 ACH. The air supply is entirely obtained from outdoor air (100%).

Table 2. Ventilation Rate in Conventional Hospital Design

| Authors          | Total supply air | Outdoor air | Recirculation of Indoor air |
|------------------|------------------|------------|-----------------------------|
| Cho et al. (2016)| 6 ACH           | 2 ACH      | Not specified               |
| Sohn et al. (2014)| 6–12 ACH       | -          | Not specified               |
| Park & Kim (2012)| 6 ACH          | -          | Not specified               |
| ASHRAE HVAC applications | 12 ACH       | 5 ACH      | Not permitted (With the exception of HEPA filter application) |

3. Target Emergency Department

3.1 Floor Plan

An existing emergency department is selected as a sample space to evaluate the effect of design factors of an emergency department on preventing the transmission of airborne pathogens. Fig.2. illustrates the floor plan of a selected emergency department. A waiting room, triage area, and acute treatment area are located near the vestibule and lobby spaces. The two spaces open to the lobby, triage area, and aisle. The aisle is connected to the general treatment area. Consequently, it is possible for an airborne pathogen to travel to any part of the emergency department. Additionally, two toilets are located in the waiting room and lobby. Generally, a toilet is maintained at a pressure lower than that of other areas to prevent unpleasant odors and the dispersion of contaminants.

Table 3. lists the floor area, volume, and ventilation condition of each space. As previously stated, the basic ventilation rate is set as 3 ACH based on identical supply and return air volume conditions. The ventilation rates of the toilets are set to 6 ACH and are only based on return air. These types of ventilation settings permit indoor airflows from the general treatment area and entrances to toilets.

4. Simulation Outline

4.1 Boundary Condition of the Base Model

Fig.3. illustrates the CONTAMW modeling of an existing emergency room. In the simulation model, the operation room and the closed areas are excluded. The doorways between rooms are set with respect to a two-way flow model (single opening). The model simultaneously reflects the incoming and outgoing airflows by using the buoyancy effect. Detailed equations with respect to the two-way flow model are provided in the CONTAMW user manual. However, the simulation is focused on the ventilation rate and airflow by pressure difference. The indoor temperature at each zone is set to 20 °C.

The measured data from a previous investigation (Jo et al., 2007) are used to determine the air-tightness of an envelope system and an entrance door. The discharge coefficient and exponent of the large opening are 0.78 and 0.5, respectively.
Table 4. shows the detailed airflow models of the openings.

| No | Type                  | Size            | Properties  |
|----|-----------------------|-----------------|-------------|
| 1  | Two-way flow          | 2.7×3.9         | Discharge coefficient: 0.78 |
| 2  | One-opening           | 2.7×2.4         | Exponent: 0.5 |
| 3  | One-opening           | 2.7×5.4         |             |
| 4  | One-opening           | 2.7×3.2         |             |
| 5  | One-opening           | 2.1×0.9         |             |
| 6  | One-way flow          | -               | 430 CMH at 50 Pa |
| 7  | Using power law       | -               | EqLAI, 1.51 cm²/m² |

The type of airborne pathogen is considered to be influenza, and its emission intensity is set based on a previous study.

In the simulation modeling, the emission intensity of the airborne pathogen is set at 1 kg/min. It is considered equivalent to approximately 9 airborne pathogens emission per minute (Marsden, 2003). Subsequently, the concentration of pathogens in a specific area is changed to a dimensionless value and finally to the number of airborne pathogens per unit volume. The quantity of air inhaled by a susceptible individual is set at 9.6 L/min. It is assumed that the sources of the airborne pathogen are located in the triage area and general treatment area based on patient circulation. Natural deposition of influenza virus at the inner surface of each zone is not considered in the simulation. It is a more conservative condition that increases the concentration of airborne pathogens in air.

A transient simulation using CONTAMW is performed to analyze the distribution pattern of airborne infection within the emergency department.

### 4.2 Simulation Cases

Simulation cases are established by considering patient circulation with respect to airborne pathogens. Table 5. presents the simulation cases in cases in which an airborne pathogen source (patient) is located in the triage area (lobby). In these cases, individuals located in the lobby (tria area) and waiting room are at a risk of airborne infection. It is assumed that a patient who releases airborne pathogens remains in the triage area for 30 min. The triage area is located in the lobby.

Base I model corresponds to a conventional condition in which an airborne pathogen source is located in the triage area and the waiting room is accessible from the lobby (tria area).

Case 1 corresponds to the modified plan type in which the waiting room is accessible from the vestibule. The conventional door placed between the lobby (tria area) and waiting room is closed.

Case 2 and 3 correspond to increased ventilation rate in the lobby and tria area. Ventilation rates in Case 2 and Case 3 are set as 6 ACH and 12 ACH, respectively.

In simulation case II, the patient who releases the airborne pathogen is located in the general treatment area. The simulation model reflects the patient circulation when the patient first stays in the triage area for 30 min and subsequently stays in the general treatment area for 4 h. Case II reflects the changed access to the waiting room. The ventilation rate in this case is 3 ACH. Cases 4 and 5 represent conditions with increased ventilation rates of 6 ACH and 12 ACH, respectively, in the general treatment area.

### 5. Results and Discussions

#### 5.1 Airborne Pathogen Sources in the Triage and Lobby Areas

1) **Base I**

With respect to the overall pressure distribution in an emergency department, negative pressure in a toilet is the main driving force for the airflow. Hence, airflows are formed from the general treatment area and outdoor areas to the toilets. Specific airflow routes that influence the airborne pathogen concentration in the waiting room and lobby (tria area) are as follows:

1. Entrance (outdoor) → vestibule → lobby → waiting room → toilet
2. General treatment area → lobby → waiting room → toilet

Fig 4. illustrates the concentrations of airborne pathogen and infection risk for Base I. The concentrations of airborne pathogen in the lobby (tria area) and waiting room increase for a period of 30 min when a patient releasing airborne pathogens (hereafter referred to as a PRAP) enters the tria area. A period of approximately 1 h is required to remove airborne pathogens in the spaces after a PRAP leaves the tria area. However, infection risk is related to the overall exposure of a susceptible person (hereafter referred to as an SP) to airborne pathogen, which increases continuously although the
PRAP leaves the triage area. The infection risks after 2 h of exposure in the waiting room and lobby (tria ge area) are 3.8% and 10.0%, respectively.

According to Fig.6., the infection risks in the waiting room and the lobby are significantly reduced to 2.3% and 6.1%, respectively.

When the ventilation rate in the lobby (tria ge area) is increased to 12 ACH, the infection risk in the waiting room is 1.3%, and that in the lobby is 3.5%. The implementation of a ventilation rate of 12 ACH in the lobby (tria ge area) is an extremely effective solution to prevent the dispersion of airborne pathogen (Fig.7.).

5.2 Pathogen Source in the General Treatment Area

1) Base II
Base II considers the condition in which a PRAP remains in the general treatment area for 4 h after visiting the triage area. As shown in Fig.8., the airborne infection risk in the general treatment area continuously increases during the patient’s occupancy period. The airborne infection risk in the general treatment area increases to approximately 24.1% after a period of 6 h after the PRAP visits the emergency area. The infection risk in the general treatment area linearly increases after the airborne pathogen concentration reaches a steady state. The simulation result indicates that the transmission of airborne pathogen from the general treatment area to the aisle is restricted, because no available opening at the general treatment area is modeled. An airflow rate of 6.7 m³/h is generated from the general treatment area to the aisle. This indicates that a maximum of approximately 0.76 infectious
particles per hour move from the general treatment area to the aisle. The transmission of airborne pathogen increases if an operable door and window exist in the general treatment area.

As shown in Fig.9, there is a negligible increase in the infection risk in the lobby and waiting room after a PRAP moves to the general treatment area.

The results indicate that, if the ventilation system works properly with an appropriate air volume, it is possible to effectively prevent the transmission of airborne pathogen between each zone. Evidently, it is desirable to increase the ventilation rate to a suitable level if the number of PRAPs increases.

3.4 Discussions

In this study, airborne infection risks in the triage area, waiting room, and general treatment area are analyzed based on the simulation results. The airborne pathogen from a PRAP is considered to be influenza. The dominant airflow pattern in an emergency department is determined by the exhaustion rates in the toilets located near the lobby and waiting room. With respect to this condition, airborne infection risks exist at a zone containing the airborne infection source and zones located on the route of transmission of airborne pathogen.

The results of the case studies indicate that the probability of airborne infection varies based on the concentration of airborne pathogens and exposure time. At a ventilation rate of 3 ACH, the general treatment area is the most dangerous zone as a PRAP resides in this area for a long time (4 h). In cases in which the general treatment area can become a source of infection, findings suggest that the probability of infecting surrounding individuals increases significantly when a PRAP remains in the room for a long period. The infection probability is based on the assumption that cumulative exposure to an airborne pathogen is sustained during a period exceeding 6 h. This indicates that medical staff working in an emergency department is most vulnerable to airborne infection and the medium of cross-infection. Patients present in the general treatment area for long periods also present the risk of airborne infection.
The triage area exhibits the second highest risk of 10.0% in the base condition. It is assumed that a PRAP remains for 30 min in the triage area. The waiting room has an infection risk of 3.8%.

The simulation results indicate that it is possible to decrease the airborne infection risk in the waiting room by changing the entrance from the lobby to the vestibule such that outside air can easily flow into the waiting room instead of the air from the lobby (triage area). However, solutions isolating the airborne pathogen source result in increased infection risks in the zones in which a PRAP remains for extended periods such as the triage area and general treatment area. Thus, it is desirable to increase the ventilation rate at the aforementioned zones where PRAPs remain for extended periods while simultaneously isolating the zones.

A useful method involves increasing the ventilation rate in a zone where the airborne pathogen is generated. In this condition, it is possible to minimize the transmission of the airborne pathogen to adjacent zones. If proper ventilation is implemented at zones near the airborne pathogen source, further transmission of the airborne pathogen can be prevented.

Particularly in the case of the general treatment area, it is considered that increasing the ventilation rate is essential to ensure that the occupancy period of a PRAP is significantly long. According to the South Korean building code (Sung, 2015), the required ventilation rate in a hospital is approximately 2.4 ACH. Thus, it is necessary to increase the ventilation rate in risky zones such as the general treatment areas, triage areas, and waiting rooms. In this case, the required ventilation rate must reflect the intensity of generation of airborne pathogens and the residing time of PRAPs.

6. Conclusions
This study analyzed the effectiveness of two design factors—namely isolating the airborne pathogen source and increasing the ventilation rate—on airborne infection control by using CONTAMW simulation. It is also expected that the results of the study can help in evaluating airborne infection risks in an emergency room and in improving the architectural design of emergency rooms within a short period.

The main results of the study can be summarized as follows:

① Potentially optimal solutions for airborne infection control are isolating the airborne pathogen source and increasing the ventilation rate.

② It is necessary to simultaneously implement isolation of the airborne pathogen source and an increase in the ventilation rate at the airborne pathogen source to prevent increased infection risk in the zone where airborne pathogens are generated.

③ The required ventilation rate should be increased in a manner proportional to the residing time of a PRAP in a specific zone.

④ Accumulated exposure time to airborne pathogens significantly influences the infection risk. Thus, medical staff, patients, and family members present in the emergency department for long periods also present higher risk of airborne infection. Appropriately designed architectural features such as proper partition installation, airflow modification among rooms, and isolated occupancy circulation can reduce the airborne infection.

⑤ This study is based on the generation of airborne pathogens by a PRAP. Considering the worst case where there are many PRAPs present, highly increased ventilation rate may be required.

The study results indicated that negative pressures in the toilets are the main driving force for the transmission of airborne pathogens. With respect to unexpected situations characterized by uncontrollable variables (such as strong wind, stack effects, strong airborne pathogen generation, or other risky human behavior), increasing the overall ventilation rate in an emergency department is also a potential solution. A future study will reflect the effects of the aforementioned external forces.

Acknowledgements
This study was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (No. 2015R1C1A1A01051740).

Authors Contributions
Chang Heon Cheong designed the research plan, performed CFD simulation, and drafted the manuscript. Beungyong Park analyzed the simulation results. Seonhye Lee reviewed the results of the study with respect to hospital environment, airborne infection, and public health. All authors read and approved the final version of the manuscript.

Conflicts of Interest
The authors declare that there are no conflicts of interest.

Note
The original value given by Marsden, A.G. (2003) is 515 pathogens per hour.
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