The Influence of Ward Ventilation on Hospital Cross Infection by Varying the Location of Supply and Exhaust Air Diffuser Using CFD

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Abstract

The SARS virus began to appear and spread in North America and Southeast Asia in the early 2000's, infecting and harming many people. In the process of examining the causes for the virus, studies on the airborne pathogen SARS virus and the way it spread were carried out mainly in the medical field. In the field of architecture, studies were done on the diffusion of air pollutants in buildings using gases such as CO₂, N₂O, or SF₆, but research on virus diffusion was limited. There were also explanations of only the diffusion process without accurate information and discussion on virus characteristics. The aim of this study is to analyze the physical characteristics of airborne virus, consider the possibility of using a coupled analysis model and tracer gas for analyzing virus diffusion in building space and, based on reports of how the infection spread in a hospital where SARS patients were discovered, analyze infection risk using tracer gas density and also diffusion patterns according to the location and volume of supply diffusers and exhaust grilles. This paper can provide standards and logical principles for evaluating various alternatives for making decisions on horizontal ward placement, air supply and exhaust installation and volumes in large hospitals.

Keywords: airborne virus; ward ventilation; hospital infection; tracer gas simulation; CFD

1. Introduction

Around 2003, SARS, a type of corona virus, began appearing in a number of areas, including Hong Kong and North America, which led to the publication of many studies dealing with the virus's paths of infection. Some of the studies that analyzed how the virus spreads employed the CFD method, which uses tracer gas to simulate virus diffusion but without carrying out an analysis of the physical characteristics of virus (Qian et al., 2006; Li et al., 2004; Gao et al., 2008). Choi et al. (2006, 2007) used a network model of airborne transmission. That study proposed a specific model for the spread of airborne pathogens, but because it assumed for its analysis that the total volume of floating microbes has a fixed numerical value and because of the disadvantages of a network model, it was not able to analyze in detail the process of airborne transmission inside a building space. An examination of the various other papers that deal with the spread of such pathogens finds weaknesses in three main areas: the subject of analysis, the evaluation, and the model. First, although airborne pathogens are the subject of these analyses, there is little attention paid to their properties, nor to how those properties compare to the properties of the tracer gas used for analyzing the diffusion of the pathogen. In other words, the studies are being carried out without a logical basis for choosing one tracer gas over another, and thus a suitable analysis of the properties of the airborne pathogens is needed. Second, existing studies use a tracer gas simulation, or a microbe model to analyze the spread of airborne pathogens. In these cases, an actual measurement or a simulation is carried out to determine the tracer gas density or the volume of floating microbes within a space, and the conclusions are based mainly on a comparison of the density or microbe volume in the various spaces. However, a truly useful model requires some idea of actual risks of infection, so a process is needed to predict the infection risk from airborne pathogens based on the tracer gas density or the volume of floating pathogens; once that is done, one can compare the various construction plans using the results. Third, there is the issue of choosing an appropriate analysis model or a mutually complementary coupled analysis. In previous studies, either a network model or a CFD model was used. The aim of this study is to analyze the physical characteristics of airborne virus, consider the possibility of using a coupled analysis model and tracer gas for analyzing virus diffusion in building space and, based on reports of how the infection spread in a hospital where SARS patients were discovered, analyze infection risk using tracer gas density and also diffusion patterns according to the location and volume of supply diffusers and exhaust grilles. This paper can provide standards and logical principles for evaluating various alternatives for making decisions on horizontal ward placement, air supply and exhaust installation and volumes in large hospitals.
characteristics of the airborne SARS virus, consider the possibility of using an analysis model coupled with tracer gas for analyzing virus transmission in a building space and, based on reports of how the infection spread in a hospital where SARS patients were discovered, analyze the infection risk using tracer gas density as well as diffusion patterns that were based on the location and volume of supply and exhaust air diffusers.

2. Airborne Transmission Analysis Model

Most major studies on the spread of air pollutants such as TVOC, formaldehyde, smell, germs, and dust within building spaces and on the more general phenomenon of air movement have relied on two types of models for their analysis. In particular, they have used either network models, such as CONTAMW, and or the CFD model. Other than the governing equations being used, the main areas in which these two types of model differ are the analysis range and the subject. In terms of the analysis range, the network model can easily consider multi-zones and analyze such things as airflow and volume between zones and the transition of pollutants. However, the network model is different from the CFD model in that the characteristics of any given zone are assumed to be fixed. That is, although in reality such factors as temperature, humidity, pressure, and pollution levels within a single zone will vary depending on their location within that space, the network model assumes these factors are well-mixed — and thus constant — throughout that entire space, and the calculations are carried out with these factors having constant values throughout the entire zone. By contrast, the CFD model allows one zone to be divided into many lattices, and because each lattice is independent, factors such as temperature, humidity, pressure, and pollution levels can be calculated differently within each lattice. Because of these different characteristics, the network model is generally used for macroscopic analysis of an entire space, while the CFD model is used to analyze detailed diffusion phenomenon within the space. In terms of the analysis subject, if the pollution source is gas, either model can carry out a diffusion analysis by inputting the physical properties of the gas being analyzed. In the case of solid particles, such as dust or microbes, the analysis is possible in the network model because it has a pollution source model for solids, but the analyses in the CFD model handles the solid particle diffusion indirectly by setting gases such as CO$_2$, N$_2$O, or SF$_6$ as the tracer gas and inputting their gaseous physical properties. On the one hand, the network model can calculate the volume and direction of current movement between zones in a multi-zone building with a ventilation system, taking into account the climate conditions and whether the ventilation openings are open or closed. On the other hand, the CFD model can show how the pollution diffuses within a space based on the layout and capacity of the ventilation system and the volume and direction of the current movement. In short, when analyzing an airborne pathogen's diffusion within a building, the two models can be used in a complementary coupled analysis, with the network model measuring the airflow rate between zones and the CFD model using those results to analyze the airborne transmission within each zone and to carry out various alternatives through simulations.

3. Possibility of Using Tracer Gas Simulation

Researches 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. Hayashi et al. (2002) reported that the normal-state respiration volume for adults during sleep was 6 liters/min with 0.7 met of activity (33.3 W/person of convective heat transfer), and the corresponding normal-state discharged air volume was 14.4 LPM. According to the physiological model of breathing proposed by Bjorn and Nielsen (2002), adults breathe about 10 times a minute, their respiration volume is 6 LPM, and their body convective heat transfer volume is 76 W. Haselton and Sperandio (1988) carried out research on heat exchange arising from convection currents between the nose and the atmosphere. In this research, it was shown that the total diameter of an adult's mouth and nose is about 0.012 m, and, during the respiratory process, the discharge temperature from the nose is 32°C and from the mouth is 34°C. Using the results of Haselton and Sperandio (1988), Qian et al. (2006) carried out a pathogen diffusion experiment and a CFD analysis by making mannequins and assuming an average wind velocity of 0.89 m/s at 32°C for discharged breezes. One problem with such an analysis is that the virus included in the discharged breezes is mixed with spray, so the precise number of pathogens being discharged from one infected person cannot be known. Because of this, studies that use the network model to analyze the diffusion of airborne pathogens postulates a special numerical value (CFU/m$^3$) as the number of pathogens included in the discharged breath, while studies that use the CFD method use a tracer gas, such as CO$_2$, SF$_6$, or N$_2$O, to represent the pathogen and then comparatively analyze its infection path and probability. It is possible to use tracer gas to represent airborne pathogens in the case of viruses. Generally, any substance that passes through a Cambridge glass fiber filter, which sifts out 99% of particles with a diameter greater than 0.1 μm, is termed a gas or vapor; this includes not only nitrogen, oxygen, carbon dioxide, and carbon monoxide, but also volatile low-molecular substances such as poisonous aldehydes, ketones, alcohols, and esters. Particles that are filtered out by the Cambridge glass fiber filter are called
particulate phase components; this category includes many organic and inorganic chemical substances. From this point of view, it is easy to see that bacteria of micro scale should be classified as particulate matter, while viruses of nano scale have the characteristics of gaseous substances, even though they actually exist in particle form. Particles that are smaller than 0.1 µm in size, regardless of whether they are solid or gaseous particles, do not easily sink in the atmosphere because Brownian motion causes them to move and spread by themselves even without external forces being applied. When external forces such as currents are introduced, those forces also move and spread the particles. In other words, although viruses are heavier than gases, they are much smaller than most solid particles and have a much higher probability of floating in the air like a gas than do bacteria, which are bigger and heavier. It is appropriate, therefore, to choose CO₂ or N₂O, which are a bit heavier than air, or some other gas with air-like properties, for use in analyzing the diffusion paths of viruses. If we also develop a method of measuring infection risk according to tracer gas density, it will, to a certain extent, eliminate the ambiguity inherent in tracer gas diffusion analysis. For a coupled analysis using the network model and the CFD model, the method of using tracer gas is a useful approach.

4. Case Analysis of Infection Risk
4.1 Subject case and infection conditions
The Prince of Wales Hospital in Hong Kong, shown in Fig. 1., was selected for our infection risk case analysis because the first patient in Hong Kong infected with SARS was hospitalized there, and the process of how the infection spread to nearby patients is well documented (Tomlinson and Cockram, 2003; Lee et al., 2003; Wong et al., 2003; Yu et al., 2005). This paper will analyze the infection path based on the hospital's reports and then compare that with the infection risk predicted by tracer gas density.

![Fig.1. Prince of Wales Hospital](image)

The index patient visited the Prince of Wales Hospital on March 4, 2003 with severe cold symptoms, and the medical staff hospitalized him in a ward without realizing he had SARS. This patient was at the hospital for eight days, from March 4 to 12. On March 12 he was diagnosed as a SARS patient and was put in isolation. Fig. 2 shows the layout and location of the ward 8A where the first patient was placed, its ventilation system, and the ventilation volume information.

Table 1. provides a chronological list of the patients who had been admitted into the same ward and those who became infected between March 4 and March 12 where the index patient was staying. Fig. 3 shows in chronological order the number and location of patients with SARS and their symptoms. During the period from the time that the first SARS patient was hospitalized to the time he was isolated, a total of 74 people had stayed in the same ward, and 30 of them became infected with SARS during or after their hospitalization. Of those 30, 14 died of SARS, while 9 died of other diseases.

![Fig.2. Floor Plan of Ward 8A and Ventilation System](image)

<table>
<thead>
<tr>
<th>Date</th>
<th>Patients</th>
<th>Infection</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 4, 2003</td>
<td>Inpatient</td>
<td>38</td>
</tr>
<tr>
<td>March 5, 2003</td>
<td>Outpatient</td>
<td>38</td>
</tr>
<tr>
<td>March 6, 2003</td>
<td>Inpatient</td>
<td>43</td>
</tr>
<tr>
<td>March 7, 2003</td>
<td>Outpatient</td>
<td>43</td>
</tr>
<tr>
<td>March 8, 2003</td>
<td>Inpatient</td>
<td>43</td>
</tr>
<tr>
<td>March 9, 2003</td>
<td>Outpatient</td>
<td>43</td>
</tr>
<tr>
<td>March 10, 2003</td>
<td>Inpatient</td>
<td>43</td>
</tr>
<tr>
<td>March 11, 2003</td>
<td>Outpatient</td>
<td>43</td>
</tr>
<tr>
<td>March 12, 2003</td>
<td>Inpatient</td>
<td>43</td>
</tr>
</tbody>
</table>

Table 2. provides the hospitalization dates of the patients. Of the 74 patients, 43 came in during the first three days, and of those, 23 became infected with SARS. In other words, of the 30 people who became infected, 23 became infected in the first three days,
which is a large majority of the infected patients. Table 2. synthesizes these results and displays the rate of infection by showing the number of patients by location. By examining Fig.3. and Table 2. together with Fig.2., which shows the layout of the ward, we can see that 20 people were at the same bay as the first infected patient, and of those, 13 were infected. This shows an infection rate of 0.65 in the same bay and 0.18 for the entire ward, which is the highest rate of infection for any location. In the case of the adjacent bay, 21 people had stayed there, and of those, 11 were infected. This corresponds to an infection rate of 0.52 within the location and 0.15 for the entire hospital. In the case of a distant bay, the infection rate was the lowest, at 0.18 within the location and 0.08 for the entire hospital. These infection rates by location show that the infection rates were higher in locations closer to the index patient. Previous studies on these infection rates indicate that there were two basic possibilities for how the infection could have spread. The first was through doctors or nurses, or medical students coming into contact with the index patient and then spreading the infection to other patients (Seto et al., 2003). However, if staff members such as doctors or nurses were the main agents of infection, then there should not have been any difference in the rate of infection by location. However, as can be seen in Table 3., there was a clear difference in the infection rate by location. Furthermore, according to the study by Yu et al. (2005), doctors and nurses had specific locations that they were assigned to within the building and so they had almost no contact with patients in other parts of the hospital. In consideration of these facts, although we cannot rule out the possibility that the infection was passed through hospital staff such as doctors, nurses, or medical students, it is considered to be of low probability. The second possibility is that the virus spreading through the air passed the infection from person to person. The results of a study by Yu et al. (2005) show that the farther away from the index patient a person was, the lower the probability of SARS infection became, and so the spread of the SARS pathogen was deduced to have occurred through the movement of air currents through the ventilation and air conditioning system. Li et al. (2004) and Yu et al. (2004) researched the process by which SARS spread in Amoy Gardens, where over 300 people became infected in 2003. Initially there were reports that an index patient had used the bathroom and then sewage overflowed into other floors, thus infecting other occupants of the building (Hung et al., 2006), but later studies carried out with more accurate research methods determined it was more likely that the SARS virus spread through air movement.

Table 2. Number of SARS Infectees and Infection Ratio

<table>
<thead>
<tr>
<th>Location</th>
<th>Same bay</th>
<th>Adjacent bay</th>
<th>Distant bay</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infectees</td>
<td>13</td>
<td>11</td>
<td>6</td>
<td>30</td>
</tr>
<tr>
<td>Non-infectees</td>
<td>7</td>
<td>10</td>
<td>27</td>
<td>44</td>
</tr>
<tr>
<td>Inpatient</td>
<td>20</td>
<td>21</td>
<td>33</td>
<td>74</td>
</tr>
<tr>
<td>Infection ratio</td>
<td>0.65</td>
<td>0.52</td>
<td>0.18</td>
<td>0.41</td>
</tr>
<tr>
<td>Total ratio</td>
<td>0.18</td>
<td>0.15</td>
<td>0.08</td>
<td>0.41</td>
</tr>
</tbody>
</table>
4.2 Analysis summary

Fig.2. shows the ward layout at the time the SARS index patient was hospitalized, the ventilation locations and volumes, and the location of the index patient within the ward, and Fig.4. shows a reference case for CFD analysis based on Fig.2. In fact, the ward 8A of the Prince of Wales Hospital was an open ward that could accommodate up to 40 people. It was not a typical ward. Accordingly, in order to predict the spread of pathogens in a typical ward, this paper assumed the four bays bound by walls on three sides and open toward the hall direction as separate rooms and carried out CFD simulations. Because the authors experimented only with the airflow direction within the ward and the pressure difference between outside and inside the room under the ventilation conditions of the reference model, there were a total of four cases. The authors' analysis will show the tracer gas distribution in the ward and AA' and BB' sections.

To examine the effect of ventilation diffuser location, and air volume, four cases were created as shown in Fig.5., and the resulting ventilation air volume conditions are as shown in Table 3. The reference case reflects the existing ventilation diffuser location, and air volume. The supply air diffuser is 0.4m×0.4m in size, and the exhaust grille is 0.4m×0.9m in size. The supply air volume is about 20% more than the exhaust air volume. Case 1 was created to explore the effect of the ventilation air volume, and while its inlet and outlet shapes and locations were the same as in the reference case, the supply air volume was set to be the same as the exhaust air volume. Case 2 and case 3 were designed to analyze the effect of the ventilation system according to its location. While the air supply in the partitioned ward was from the middle of the reference ward and the exhaust was located at the boundary with other wards, with cases 2 and 3 the exhaust was located in the middle of the room and, instead of the existing air supply opening, a supply air diffuser 0.075m×4.8m in size was located at the boundary with the other wards. The air supply and exhaust volumes in case 2 were set to be the same as those of the reference case, while those in case 2 were the same as those in case 1.

Thus the four cases each have different air supply and exhaust characteristics, and accordingly, their general airflow directions will be different as well. Table 4. displays the general boundary and calculation conditions regarding air supply, exhaust, and breathing for the analysis of virus diffusion. To analyze virus diffusion for each case, the CFD model releases tracer gas from the index patient's location. Because the virus spreads through the oral or nasal cavity of a patient during breathing, normal breathing was assumed, and the boundary conditions for tracer gas were set to be the same as for normal breathing, as shown in Table 4. To distinguish the gas from ventilation air, N₂O gas was used. The boundary conditions for normal breathing were based on the framework set in previous studies by Hayashi et al. (2002), Bjorn and Nielsen (2002), Haselton and Sperandio (1988), and Qian et al. (2006).

4.3 Infection risk according to tracer gas density

As shown in Fig.6., when current conditions are applied to the reference case, we can see that the N₂O gas, which represents breathing air, spreads to the entire ward once it is emitted from the index patient's location. In the reference case, the air supply comes from the center of the partitioned ward, and the air leaves at the boundary of the ward. Because the air supply volume is greater than the exhaust volume, there is a difference in left over air volume (supply - exhaust air) in the partitioned wards, which in turn creates a density difference between the wards. Because of this, when we examine the contour line that appears in Fig.6., the air volume being supplied at the center of the same bay is greater than the exhaust volume and causes the virus tracer gas N₂O to go beyond the central air supply of the adjacent bay and push out to distant bays 1 and 2. When the densities of the partitioned wards are compared, the average density of the index patient's bay was 45.419E-04 ppm; of the adjacent bay, 5.861 E-04 ppm; of distant bay 1, 2.027 E-04 ppm; and of distant bay 2, 1.054 E-04 ppm. Excluding the first bay, each ward showed a density difference with respect to the tracer gas. This
is because the inflow volume of tracer gas from the first bay is determined by the pressure and distance difference of leftover air volume in each ward.

\[ P = \frac{C}{V} \left( 1 - e^{-\frac{d}{D}} \right) \]  

(1)

The quantum, \( q \), represents the generation rate of infectious doses. Exposure to one quantum gives an average infection probability of \( 1 - e^{-1} \). Based on the knowledge of infection dose (the number of organisms required to cause infection), the risk of airborne infection and ventilation rate per person can be correlated by Wells-Riley equation (Riley et al., 1978). The Wells-Riley equation is set up on the assumption of a well-mixed and steady state condition. Here, using CFD the authors can obtain the concentration of infectious particles at a certain point, which allows derivation of spatial distribution of infection risk. It does not require the assumption of well-mixed conditions. The spatial variance of infection probability is similar with the distribution of mass fraction of the tracer gas and a high concentration denotes a high risk (Gao et al., 2008). According to the results of these studies, the actual ratio of patient infection within the ward and the tracer gas concentration were compared and Fig.7. and equation (2) were derived.

\[ y = 0.132 \ln(x) + 1.404 \]  

(2)

When these average N\(_2\)O densities of the wards are viewed together with the infection rate of SARS by location, as shown in Table 2., we can see that as the average density increases so does the infection rate. In other words, the index patient's bay, which had an N\(_2\)O average density of 45.419E-04 ppm, had the highest infection rate, 0.65; whereas the adjacent bay, where the average density was 5.861E-04 ppm, had an infection rate of 0.52; and the distant bay, where the average density was 15.40E-04 ppm, had the lowest infection rate, 0.18. Fig.7. shows these results as a distribution map and a trend line. Looking at the trend line, we can see that the infection rate shows average density as an independent variable and is expressed as a logarithmic function, as in Equation (2).

4.4 Analysis on the difference between supply and exhaust airflow rate

Generally, partitioned wards have a higher volume of air supply than of air exhaust. This causes static pressure within the space, and the leftover volume of air exits through existing cracks, such as various openings, door or window crevices, and fissures. With the reference case, the air supply volume is similarly about 20% greater than the air exhaust volume. This causes the leftover volume of air to move to low-pressure areas within the ward space. In case 1, however, the air supply and exhaust volumes are set equally, so there is no leftover air. In other words, the same amount of air leaves the ward as is supplied to
the ward. When $\text{N}_2\text{O}$ is emitted from the index patient's location in case 1, $\text{N}_2\text{O}$ spreads to the entire ward, as can be seen in Fig.9.(a). Although the air supply and exhaust in case 1 occur in the same locations as those in the reference case, the movement of current due to pressure differences between the partitioned wards occurs only weakly because there is no leftover volume of air. Looking at the contour line that indicates density in Fig.9.(a), we can see that the volume of air being supplied at the center of the index patient's bay is the same as the volume of air being exhausted, and only part of the $\text{N}_2\text{O}$ is transmitted to the adjacent bay, distant bay 1, and distant bay 2. When the density levels of the partitioned wards are compared, the average density of the initial bay is shown to be 12.057E-04 ppm; of the adjacent bay, 1.911E-04 ppm; of distant bay 1, 0.795E-04 ppm; and of distant bay 2, 0.675E-04 ppm. When case 1 is compared to the reference case, we can see that in all the partitioned wards, the density of $\text{N}_2\text{O}$ is reduced to less than 50%. This is mainly because there is no movement of air from the index patient's bay to other partitioned wards, and so $\text{N}_2\text{O}$ is thus accumulated within the initial bay, and much of the polluted air in the same bay space is exhausted. Also, because there is no great pressure difference between the partitioned wards, there is less $\text{N}_2\text{O}$ transmitted from the initial bay to the other wards than in the reference case.

4.5 Analysis according to air diffuser location

The air supply and exhaust volumes in case 2 match those of the reference case, but the air is exhausted at the center of the ward and it is supplied at the boundary with other partitioned wards. The ventilation locations in case 3 are the same as those in case 2, but the air supply and exhaust volumes are set to be the same so there would be no leftover volume of air. With both cases, unlike the reference case, the air comes from a supply air diffuser. When $\text{N}_2\text{O}$ is emitted from the index patient's location in cases 2 and 3, the $\text{N}_2\text{O}$ spreads throughout the ward, as can be seen in Fig.9.(b) and Fig.9.(c). With case 3, shown in Fig.9.(c), because the polluted air is exhausted at the center of the ward and new air comes in through the supply air diffuser at the boundary, $\text{N}_2\text{O}$ is isolated in the index patient's bay and cannot spread. Because of this, the average density of the initial bay is 14.853E-04 ppm, which is higher than that of case 2, where the air supply is greater than the exhaust, but because the efficiency of isolating polluted air is high in case 3, the average density of the adjacent bay is 0.945E-04 ppm, that of distant bay 1 is 0.607E-04 ppm, and that of distant bay 2 is the lowest of all cases, at 0.375E-04 ppm. In case 2, the $\text{N}_2\text{O}$ being emitted exits at the center of the ward, and the gas that would otherwise spread out is pushed inward by the supply air diffuser. As shown in Fig.9.(b), however, because the supply of air is greater and produces a leftover volume of air, the gas eventually diffuses to other partitioned wards. Because of this, the average density of the index patient's bay is 21.274E-04 ppm, higher than that of case 1. The average density of the adjacent bay is 2.291E-04 ppm; of distant bay 1, 1.422E-04 ppm; and of distant bay 2, 0.934E-04 ppm, which is a fairly high level. When the analysis results are considered all together, we can see that the current movement changes according to ventilation diffuser location and the volume of air supply and exhaust. In particular, an imbalance in air supply and exhaust produces a static pressure in parts of the room, and the leftover air in the room is transmitted to other spaces, thus spreading the index patient's exhaled breaths. It was also shown that when air is exhausted within the partitioned room and air is supplied from the boundary area of the room, the index patient's exhaled breaths do not spread to other spaces but are isolated and exhausted.
5. Conclusions and Future Work

The SARS virus appeared in North America and Southeast Asia in the early 2000s, infecting and harming many people. Researchers, mainly in the medical field carried out studies of how the airborne pathogen that causes the SARS virus is spread. In the field of architecture, a variety of studies were done on the diffusion of air pollutants in buildings using gases such as CO$_2$, N$_2$O, or SF$_6$, but research on the diffusion of viruses in buildings was limited. There were some discussions on how the virus might diffuse in structures, but they were done without accurate information about the characteristics of the virus. Accordingly, this paper set out to analyze the physical characteristics of viruses and to propose a logical basis for using a tracer gas and analysis models in examining the diffusion of viruses. Furthermore, by using the reports on how the SARS infection spread at a hospital where people first became sick with SARS, the authors were able to analyze the diffusion patterns of the virus according to ventilation diffuser location as well as the infection risk based on tracer gas density. The research can be summarized as follows. With pathogens that can be airborne, documentary research found that, although the viruses have a density greater than that of water, they exist in various particle forms that can float in air. Furthermore, in contrast to bacteria and rickettsia, because their size is nano-scale, Brownian motion allows them to move like gas molecules through the air. In other words, although they are solids, they can be classified as gaseous substances because of the way they diffuse in the air, and, accordingly, it is reasonable to use tracer gases in analyzing the virus diffusion path or the infection risk. Using the case of a hospital where a patient infected with SARS was hospitalized and infection spread, the infection risk was analyzed according to the density of tracer gas, and the results showed that the higher the density of tracer gas, the higher the infection risk was. The infection rate indicated by the tracer gas density could be expressed as a logarithmic function. This function showed that the average density of tracer gas corresponded to an infection rate of 86.6%. It is believed that using this trend line will make it possible to perform a quantitative evaluation of virus diffusion and infection risk for various future hospital designs.

The authors have seen that interior air movement changes according to ventilation diffuser location, and air supply and exhaust volumes. In particular, an imbalance between the air supply and the exhaust can cause a static pressure within a room, which can cause interior air to be transmitted to other spaces; during that process, virus particles from an infected person's exhaled breath can spread. It was also found that, with respect to ventilation location, if air is exhausted within a partitioned room and supplied from the boundary of that room, an infected person's exhaled breaths could be isolated in that room and vented out.

This paper can suggest standards and logical principles for evaluating various alternatives for making decisions on horizontal ward placement, air supply and exhaust installation, and air volumes in high-rise hospitals.

In future studies, the effect of the shape of diffuser and grille with the same or different location should be carried out in detail as part of a follow-up study. And the authors will consider comparing and verifying the results of the paper with particle simulations in the CFD field.

References