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Research Article

Estimating ventilation and replacance needs based on sensory pollution load to improve perceived air quality in therapeutic spaces: Case of inpatient wards of a hospital

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Abstract

Background and objectives: The study of the sensory pollution load and perceived air quality has been introduced as one of the methods of evaluating indoor air quality in non-industrial environments. This method is also used to estimate ventilation needs. This study aims to recommend the required ventilation rate according to the SPL to improve the PAQ in a therapeutic space.

Methods: Ventilation rate and time which is required for 98% of the old air to be exhausted at that rate were calculated in 9 rooms in inpatient wards of a hospital. High dissatisfaction had been reported from these spaces. The SPL of individuals, building materials, and ventilation systems were estimated using the Fanger model. The required ventilation rate was recommended and compared with the existing ventilation rate, WHO, AIA, and ASHRAE standards.

Results: In the studied spaces, the measured flow rates and air changes per hour were from 28 (minimum) to 178 (maximum) l/s and 2 to 7 ACH. These values were in accordance with the AIA standard, less than the values calculated through the ASHRAE (39-117 l/s) and WHO (80-560 l/s) standards, and Fanger model (51-393 l/s & 3-13 ACH).

Conclusion: It seems that considering sensory pollution loads is a practical, simple, and fast method for estimating ventilation needs to improve perceived air quality and users' satisfaction and performance while reducing the energy consumption required to meet the ventilation rate. It does not have some shortcomings and limitations of other standards and methods. In existing hospitals, it can be used as a method to evaluate the effectiveness of the ventilation systems as well as the perceived air quality. Besides, the importance of adopting some strategies to reduce the sensory pollution load was emphasized.

Keywords
Perceived air quality (PAQ), Sensory pollution load (SPL), Replacance, Indoor air quality, Ventilation, Health care facilities

Background and objectives

ASHRAE[1] has defined the acceptable indoor air quality as a condition in which the concentration of any known pollutants in the air does not exceed the limits set by cognizant organizations, and at least 80% of people, do not express dissatisfaction with the situation. This definition in addition to the health criterion (concentration of pollutants), also refers to people's satisfaction. However, to determine the indoor air quality level only the components of indoor air (pollutants) are usually measured, instead of assessing the effect of indoor air on individuals and users' satisfaction with indoor air quality. On the other hand, according to researches of Fanger[2] and Bluyssen & Fanger[3] individuals especially in non-industrial spaces have often complained about air quality when the pollutant concentration is at a level that cannot be measured with existing tools.

Even if the ventilation rate is following the existing ventilation standards, air quality may not be acceptable to people

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In fact, different compounds in indoor air can have negative sensory effects on people by affecting their sense of smell. Given the above, as well as due to the variety of compounds in indoor air, problems and costs of measuring them, interactions between compounds, and lack of sufficient toxicological and sensory information about the mixing of air compounds[4], physical and chemical measurements are not always able to fully assess the indoor air quality or to determine the cause of people's complaints about indoor air quality. Therefore, people can be used as a tool for measurement and judgment on the indoor air quality, as well as the determination of the required ventilation rate. Wargsky, Fanger, et al[5] examined the relationship between perceived air quality and people's performance in an office building.

Accordingly, two units of "olf" and "decipol"[2]; was introduced by Fanger to determine how individuals perceive air. "Olf" (derived from the word "olfactory") is a unit for determining the quantitative strength of an air pollutant source, and "decipol" (derived from the word "pollution") is a unit for quantifying perception of air pollution[6]. One "olf" Fanger et al research is the bio effluent emission rate from a standard person. The standard person in this definition is a sedentary adult in thermal comfort who works in an office or any other similar non-industrial workspace. Any other source of pollutant production is defined as a number of standard individuals who cause similar dissatisfaction. Individuals, human activities, cigarette smoke, cooling, heating, and air conditioning systems, electronic equipment, and materials are among the pollution sources in non-industrial buildings. One "decipol"[6] is the pollution caused by a standard person (1 olf) that is ventilated with clean air at a rate of 10 liters per second.

"Olf" and "decipol" are related according to equation 1. The relationship between people's satisfaction and "decipol" is presented in Equation 2. In this way, the amount of ventilation required based on the "olf" and "decipol" values can be achieved through Equation 3. The "Replacance"[7] which affects ventilation system designing indicates a fraction of air molecules at a specified time which was not in the room at a reference time. This indicates that for example, with one ACH of outdoor air supply, after 1 hour, only 63% of new air would be in the room. Therefore, about 8 hours would be required to exhaust all of the old air at this rate[8].

The present study aims to estimate the required ventilation rate according to the SPL and to improve the PAQ in a therapeutic space. For this purpose, the SPL values of main sources including individuals, ventilation systems, and building materials (in olf), and air change per hour were calculated. Then, the ventilation rate required to improve the PAQ was estimated according to the SPL. The results were compared with the measured ventilation rate and WHO, AIA, and ASHRAE ventilation standards.

(E1) $C_{outdoor} + G/Q = C_{indoor}$ or $G = 0.1 \cdot Q \cdot (C_i - C_o)$

(1 decipol $= 1$ dp $= 0.1$ pol $= 0.1$ olf/l s^{-1})

(E2) $PD = 395.\exp(-3.25 \cdot c^{-0.25})$ for $C \leq 31.3$ Decipol[2,6] ($PD=100\%$ for $C>31.3$ decipol)

(E3) $Q = 10 \times (G / C_i - C_o) \times 1/E_v$

(9)؛ (10)

Q= Ventilation rate (l/s)

G= total SPL (olf)

C_i= PAQ (decipol)

C_o= PAQ (decipol)

E_v= ventilation effectiveness

PD= percentage of dissatisfaction

(If we determine the SPL according to olf/m^2 floor, the ventilation rate will be according to l/s.m^2 floor).

Methods

The research steps are shown in Figure 1.

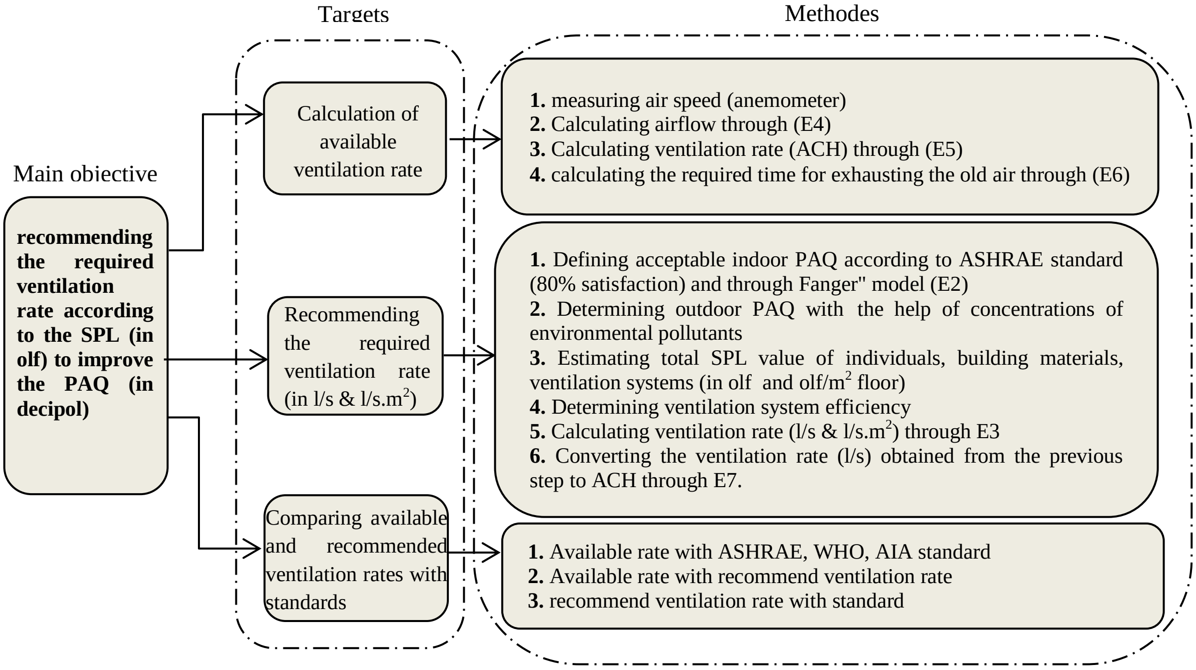

Figure 1: Research steps

Case study Selection

Different hospital wards have different functions and therefore need different conditions in terms of temperature, humidity, air pressure, and ventilation rate. Thus, only inpatient wards were focused on. Since the SPL can change according to the sources in the space- the ventilation system for example- as the studied building changes so do the conditions and some mediating variables. In this study, only one hospital was focused on.

The selected hospital building is designed as a three separate block. The inpatient wards are located on floors one to six of one of these blocks. Therefore, the inpatient wards have no connection with other spaces and are not affected by other spaces. Among different spaces in the inpatient wards, nine rooms were examined (Table 1). Most dissatisfaction had been reported from these rooms.

Table 1: Specifications of measured spaces and vents in the selected hospital

Room / Parameter	Phototherapy	P.NICU	LDR	4-bed Labor room	3-bed Labor room	NICU	2-bed hospital room	Pre-eclampsia	Temporary hospitalization
Vent type/ emplacement	wall	wall	Ceiling	Ceiling	Ceiling	Ceiling	wall	wall	Ceiling
Number of vent	1	1	1	4	2	2	1	1	1
Number of slit in each vent	-	-	3	3	3	3	-	-	3
cross sectional area of Slits (cm)	-	-	28.7× 1 18.5×1 9.8× 1	26×1 17×1 10×1	28.7× 1 18.5×1 9.8× 1	28.7× 1 18.5×1 9.8× 1	-	-	26×1 17×1 10×1
cross sectional area of Vent	23×27	23×27	-	-	-	-	23×27	23×27	-
Total number of measured points in each vent	9	9	20	20	20	20	9	9	20
Room Volume (m^3)	55.66316	56.21084	57.56716	112.95228	82.9136	113.1312	56.27916	58.31812	72.98704
Air flow (m3/s)	0.0285352	0.0313618	0.032117	0.1781975	0.06981025	0.0639615	0.111573786	0.0496674	0.036587

1. Calculation of ventilation rate and time to exhausting 98% of the old air

In the first step, the ventilation rate was calculated. First, the speed and temperature of the airflow in the AHU (Air Handler Unit) air vents of the rooms were measured using the rotating vane "anemometer" AMV07 model made by PROVA Company in Taiwan. For this purpose, the airflow speed was measured at 8 points per slit with the help of the mentioned device (for smaller slits at 4 points, and a total of 20 points for three slits of each vent) (Table 1). The average of the values was defined as the airflow velocity at each slit.

For ceiling vents (Table 1), the airflow rate at each slit was calculated through multiplied the area of that slit by the average air velocity at the slit (Equation 4). The total airflow rate of each air inlet (in cubic meter per second) was calculated from the sum of the flow rate of slits of that air inlet. For wall vents, the airflow speed was measured in 9 points at equal distances with the help of the device (Table 1). The average of these values was considered as the airflow speed in that vent. The total airflow rate in each vent (in cubic meter per second) was calculated by multiplying the average air velocity by the free space area of each vent. For rooms or spaces with multiple air vents, the total airflow rate (in cubic meter per second) was calculated from the sum of the airflow rate of each vent. The number of air changes per hour was calculated using Equation 5. The area and height of each space were extracted from the architectural plans and the volume of the rooms was calculated.

Based on the number of air changes per hour, the time required for the old air to outflow from each room was calculated using the concept of replacance in Equation 6. In the present study, the "replacivity value" was considered 98%. Thus, the time required to remove 98% of the old air was calculated for each space.

All measurements were performed at peak temperature and pollution conditions. Measurements were repeated twice.

(E4[11,12]) $Q = V \times A$

Q= The amount of airflow in the air vent (m^3/s)

V= Air velocity (m/s)

A= cross-section area of the vent (m^2)

(E5[13]) ACH (Air Change Per Hour) = $Q \times 3600 / V$

V= volume of the room (m^3)

Q= The amount of airflow in the air vent (m^3/s)

(E6[7]) Replacance (%) = $1 – 0.368^{XN}$

X= Time from start of run

N= rate of air input (ACH)

2. Estimating air ventilation requirement to improve the PAQ given the SPL

At this stage, the ventilation rate required to achieve acceptable indoor air quality was predicted through Equation 3. According to the ASHRAE standard, acceptable indoor air quality is a condition in which 80% of people do not express dissatisfaction. In this case, according to Equation 2, the PAQ (C_i) in Equation 3, was considered 1.4 decipol.

According to researches ef Bienfait et al[9], Stellman[10] and CEC[14] , if the average yearly concentrations of environmental pollutants including CO_2, CO, NO_2, and SO_2 is between 700, 1-2, 5-20, and 5-20 (mg/m^3) respectively, the outdoor PAQ (daily average values in decipol) will be <0.1 (in a high-quality city).

Based on the information obtained from the "Department of Environmental Protection" regarding the concentration of mentioned pollutants (CO_2, CO, NO_2, SO_2), the perceived quality of outdoor air is often in the high-quality range. The air in the area of the hospital building has also been described as clean due to the distance from urban pollution sources. Besides, at the decipol scale provided by Fanger[5], the maximum PAQ in cities is considered to be 0.1 decipol. Therefore, the perceived quality of the outdoor air (C_O) in Equation 3 was considered equal to 0.1.

To estimate the strength of air pollutant sources (SPL in olf or G) in Equation 3, several groups of major sources including individuals, building materials, and ventilation systems, were considered. Based on studies by Fanger et al[3], the total SPL load in each space was predicted approximately by the simple sum of the "olf" values of each pollutant.

According to researches ef Bienfait et al[9], Stellman[10] and CEC[14], the SPL (olf/person) of individuals based on the metabolic rate can be determined as follow: for not smoker sedentary people (1 or 1.2-1.5 MET), SPL is about 1 olf. For low physical exertion (3-4 MET), SPL is about 4 olf. For medium physical exertion (6 MET), SPL is about 10 olf. For high physical exertion (10 MET), SPL is about 20 olf.

The SPL of individuals in each room (in terms of olf) was estimated based on the maximum capacity of the room (number of beds) and the minimum number of personnel. The level of activity (metabolic rate) of patients and staff was determined according to the ASHRAE standard[15].

The SPL of all non-living sources in the building was described as "olf per square meter of the floor." For many materials, there is little information about the SPL in Olf per square meter. Therefore, the SPL in the whole building (materials, furniture, ventilation system, dust trapped in filters, and office equipment such as personal computers) in terms of "olf per square meter" was considered. In the present study, assuming low pollution in the building, the SPL of these sources per square meter of the building was considered to be 0.1 olf[16]. The total SPL was calculated from multiplying this value by the floor area.

According to research of Stellman[10], the ventilation efficiency in the breathing zone can be obtained by calculating temperature differences between air supply and breathing zone. It also indicates that in mixing ventilation, if the temperature difference between air supply and breathing zone is <0, the ventilation system efficiency will be equal to 0.9-1.

The ventilation system efficiency in Equation 3 was considered equal to 0.9. This value was obtained by subtracting the supply air temperature (measured by anemometer) from breathing zone air temperature (measured by a German TFA humidifier and thermometer).

According to the values obtained from the proposed ventilation rate through Equation 3, the number of air changes per hour was calculated using Equation 7.

(E7[13]) $ACH = Q \times 3.6 \ / V$

Q= ventilation rate (l/s)

V= volume of the room (m^3)

(From equation E5, we can deduce this equation. To convert Q from l/s to m^3, the numerator in equation E5 must be multiplied by 1/1000).

The ventilation need per square meter of the surface was also estimated for each room. for this purpose, the estimated Maximum Occupancy or net occupiable space (p/100 m^2) was considered 10 people per 100 square meters (0.1), according to ASHRAE standard (ASHRAE 2001). For each group of users (staff, patients, companions), the people's SPL in terms of "olf per square meter of surface (olf/m^2. Floor) was calculated through the multiplication of this number in the values mentioned above about the SPL (olf/person) of individuals based on the metabolic rate. The SPL estimation of non-living sources (olf/m^2. floor) was done according to the method described above.

3. Comparing available and recommended ventilation rates with the rates set by standards

Finally, the available and recommended ventilation rates were compared with the required ventilation values calculated based on some of the most important standards.

For this purpose, the World Health Organization (WHO) standard[17] was considered. According to this standard, at least 80 liters per second of the ventilation rate is necessary per each patient. AIA (The American Institute of Architects) guideline[18] has set the minimum 2 ACH of fresh air for the patient and infant rooms, and 3 ACH for delivery spaces. ASHRAE (19) has determined the amount of outdoor air needed to provide acceptable indoor air quality in some hospital spaces[13] liters per second per person for the patient's rooms). This standard states that these values have been selected to dilute "human bio effluent" and other pollutants, along with appropriate safety margins and to consider diversity in peoples' health status and activity levels. The processes that produce contamination may require more ventilation rate.

Results

For the studied spaces, the available ventilation rate (according to section 1 of the research method) is presented in the first section of Table 2. The recommended ventilation rate to achieve 80% satisfaction (according to section 2 of the research method) is presented in the second part of Table 2. The ventilation rates set by some of the most important standards (according to section 3 of the research method) is presented in the third section of Table 2.

The recommended ventilation rate values differ from the available one and the values determined by the standards.

In most of the studied spaces, the available ventilation rate (in ACH) is in accordance with the AIA standard. But satisfaction is not provided. There is a difference of about 19 to 230 l/s between the available ventilation rate and the recommended one.

If we calculate the total required ventilation rate according to the ASHRAE standard (13 l/s per person), depending on the number of patients in each space, between 39 l/s (minimum value) to 117 l/s (maximum value) is obtained. If we calculate the total required ventilation rate according to the WHO standard (80 l/s per person), depending on the number of patients, between 80 (minimum value) to 560 (maximum value) is obtained. Therefore, there is a difference between the WHO and ASHRAE standards, from 41 to 443 liters per second in the amount of ventilation required for each room.

Through the proposed method, values of 51 to 393 l/s were obtained for the total amount of ventilation required. These values are closer to the values calculated through the ASHRAE standard. Except in one case where the amount of SPL (olf) and dissatisfaction were very high.

Table 2: Available and recommended ventilation rates in the study spaces in the selected hospital building (Research findings)

Ventilation rate \ Room		Phototherapy	P.NICU	LDR	4-bed Labor room	3-bed Labor room	NICU	2-bed hospital room	Pre-eclampsia	Temporary hospitalization
1.Available	l/s	28.5352	31.3618	32.117	178.1975	69.81025	63.9615	111.5737857	49.6674	36.587
	ACH	1.8	2.0	2.0	5.7	3.0	2.0	7.1	3.1	1.8
	Time for exhausted old air	02:07:14	01:56:54	01:56:54	00:41:20	01:17:28	01:55:22	00:32:54	01:16:35	02:10:07
2.Recommendation	l/s	93.82	51.29	120.02	393.06	298.51	102.81	68.39	69.01	56.41
	ACH	6.07	3.28	7.50	12.53	12.96	3.27	4.37	4.26	2.78
	$l/s. m^2$ *	3.4	2.6	11.1	10.2	10.2	2.6	3.4	3.4	2.6
3.Standards	WHO	560 l/s	240 l/s	80 l/s	320 l/s	240 l/s	400 l/s	160 l/s	160 l/s	240 l/s
	AIA	2 ACH	2 ACH	3 ACH	3 ACH	3 ACH	2 ACH	2 ACH	2 ACH	2 ACH
	ASHRAE	117 l/s	52 l/s	39 l/s	78 l/s	65 l/s	104 l/s	78 l/s	78 l/s	52 l/s

* Ventilation requirement per square meter of the floor to provide 80% satisfaction with indoor air quality, assuming low pollution in materials, ventilation systems, and building equipment (0.1 olf per square meter), and high outdoor air quality (0.1 decipol). The ventilation system efficiency was calculated 0.9 in the selected building. Bio effluent caused by each group of people in each space (in olf per square meter) was considered.

Discussion & Conclusion

The present study aimed to estimate the required ventilation rate according to the SPL and to improve the PAQ in a therapeutic space. In this regard, the use of a method to describe pollutants (odor intensity) that we are not able to measure by conventional methods, how to deal with it, description of indoor air quality based on PAQ, and estimation of ventilation requirements were considered.

Unacceptable indoor air quality (including high odor intensity) can influence the process of treating patients, staff efficiency, and people's health (e.g., cause migraine, eye irritation, and fatigue, etc). Odor management and satisfaction increasing would improve nurses' working conditions and could have indirect effects on nurse job satisfaction, reduction in burnout, efficiency, and health. If a solution is not considered for staff satisfaction, they may intervene (such as opening windows, etc.) which can increase the building's energy consumption.

The highest dissatisfaction was reported with the "4-bed labor room", although, according to the results, the existing ventilation rate is in accordance with the standards, and old air exhaust time (about 41 minutes) is appropriate. The reported dissatisfaction even in well-ventilated rooms suggests that existing standards for providing acceptable indoor air quality and existing methods for assessing indoor air quality alone may not be sufficient.

However, it seems that determining the minimum amount of ventilation rate alone does not guarantee the optimal quality of indoor air for all environments. With high SPL, increasing the ventilation rate is only being somewhat helpful. Besides, in some cases, the amount of SPL and therefore the amount of required ventilation rate according to Equation 3, gives high and Unattainable values. Therefore, setting maximum limits for olf in each space seems necessary. This can lead to a reduction in energy consumption too (for example, by providing the desired amount of ventilation, which can be useful in reducing the load of heating and ventilation systems). In this regard, appropriate design and placement of spaces, patient grouping (separation of wards) based on the patient's condition, and determining the per capita space for each group of patients according to the conditions of each one can be useful.

It should be noted that it seems the most effective way to reduce the SPL of the building in the post-construction stage is controlling indoor pollution sources and replacing some materials if possible, and in the pre-construction stage is the avoidance of using waste materials that lead to contamination.

On the other hand, in calculating the required ventilation rate through Equation 3, people's adaptation can result in lower values. But in spaces where people are constantly coming and going the first exposure and perception of the situation is important. Besides, according to researches, the odor intensity may decrease for people due to their adaptation after a while, but its effects such as irritation of the respiratory tract may remain.

Overall, despite some limitations, the Fanger equation seems to be a practical tool for estimating ventilation requirements to provide acceptable indoor air quality from a user perspective as well as assessing air pollution in terms of their effects.

It offers an optimal limit for the ventilation rate (which is close to the ASHRAE limit) and as a result, compared to the values set by other standards, it is likely to reduce energy consumption to meet the ventilation needs. Since it offers ventilation rates in l/s per square meters (not the number of patients), ventilation needs can be estimated accurately, fast, and with low cost, both in the design phase and if some changes need to be made to the hospital space after that. The method introduced in this article can be useful in evaluating the effectiveness of hospital ventilation systems.

It does not have some shortcomings and limitations of other standards. Among the shortcomings of most of the existing standards regarding the determination of the minimum supply of outdoor air, we can mention the following: considering people as the only source of pollution; Lack of attention to the indoor air quality required for a given space according to the type of space use; Lack of specified classification of air quality for the spaces we intend to ventilate and the total pollution load in the occupied spaces; Lack of attention to the air quality entering the building (available outdoor air quality). In the present study, it was tried to estimate the ventilation needs according to the type of space use and the situation of patients in each space in terms of metabolic rate and pollution load, with the help of the Fanger model. Other sources as well as outdoor air quality were also considered in assessing the ventilation rate.

So far, this method has not been used accurately in therapeutic spaces. On the other hand, due to the lack of information about the SPL of many common materials in indoor spaces and citing the values determined by other researchers in this paper, further research seems to be necessary to determine the SPL.

Many studies have been done on indoor air quality and ventilation in the hospital. A number of these studies have evaluated perceived air quality in different hospital space, and the effectiveness of ventilation systems. In these studies, parameters are measured that do not fully reflect the indoor air quality and the cause of people's complaints about air quality. In evaluating the efficiency of the ventilation system less attention has been paid to the ventilation needs to improve the perceived air quality. Besides, the pollution of ventilation systems has been less considered. However, contamination of ventilation systems has been proven in various studies. In a study,[1] a significant level of amoebae cysts contamination of cooling systems with excelsior filters in various hospital wards was observed.

In some studies[2], nurses' perceptions of the odors of various hospital settings including hospital rooms were investigated through survey research. Rooms that had greater odor intensity and were perceived as more uncomfortable were rated. In some studies,[3] the effect of other parameters such as temperature and humidity on the users' perceived air quality has been considered. But no solution has been offered.

In some researches, different types of ventilation systems have been studied and compared from the perspective of controlling factors such as the spread of infection and thermal comfort. The advantages and disadvantages of these systems have been discussed in these aspects. In these studies, less attention has been paid to the odor intensity and dissatisfaction of individuals (which is emphasized in the definition of acceptable indoor air quality in ASHRAE standard), as well as the ventilation rate required to control the situation.

For instance, In some studies[4], hospital wards were investigated with three different ventilation systems including displacement, mixing, and downward ventilation. A Displacement Ventilation (DV) system was proposed to solve the serious odor problem in hospital wards by some researchers[5]. But they had not offered any values to the ventilation rate to the extent of staff satisfaction.

In small-scale assessments in a climate chamber, to model the actual conditions, the results of the perceived air quality

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[1] Refer to research of Mosayebi et al[20]

[2] Refer to researches of Horiguchi et al[21] and Itakura & Mitsuda[22]

[3] Refer to research of Roelofsen[23]

[4] Refer to researches of Qian et al[24] and Berlang et al[25]

[5] Refer to research of Choi et al[26]

estimation may be beyond reality and exaggerated. The present study was performed in the real spaces of a hospital and on a full-scale assessment.

Authors' contribution

Part of this article has been extracted from the first author's Ph.D. thesis under supervision of the second, third and fourth authors.

Conflict of Interest

There was no conflict of interest.

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