Original Article

CO₂ concentration visualization for COVID-19 infection prevention in concert halls

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Abstract

Objectives: For preventing coronavirus disease 2019 (COVID-19) clusters, avoiding the three C's, which are closed spaces with poor ventilation, crowded places with many people, and close contact for conversation, is important. The CO₂ concentration in a room indicates the ventilation status, number of persons present in the room, and their kinetic strength or activity intensity. The real-time monitoring of CO₂ concentration in a room will enable instantaneously confirming whether ventilation is sufficient. **Methods:** This study investigated monitoring CO₂ concentration in real time during a concert and instantly indicating the measurement results on a display. **Results:** The average CO₂ concentration during the performance was confirmed to be 505.6 ppm with the maximum value 575 ppm, and these values were in line with the estimated value given by the Ventilation Simulator designed by the Occupational Hygiene and Ergonomics Section of the Japan Society for Occupational Health. The CO₂ concentration visualization has the benefit of providing a sense of security to the concert audience, musicians, and concert organizing staff during the performance. **Conclusion:** For preventing COVID-19 clusters, it is important to take multiple and comprehensive countermeasures considering concert event-specific infection routes; visualizing CO₂ concentration is one effective preventative measure against airborne (droplet nuclei) infection. The CO₂ concentration visualization based on prior estimation is expected to become part of the standard operational procedure of concert venues.

Keywords: airborne infection, CO₂ concentration visualization, droplet nuclei infection, ventilation

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Introduction

According to the Act on Maintenance of Sanitation in Buildings, commonly known as the Building Management Law, promulgated and enforced in 1970 in Japan, buildings used as entertainment show venues, department

stores, stores, offices, schools, and other similar functions having considerable scale are referred to as specified buildings and owners or other related persons of specified buildings are obliged to manage the air and other environment factors based on the management standard of environmental sanitation for buildings. For non-specified buildings to be used by a great number of people, the owners or others are required to make efforts to manage the air and other environment factors in accordance with the same standards. The management standards of environmental sanitation for buildings stipulate that air qual-

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ity should be measured a minimum of every 2 months, and specify standard air quality values and measurement methods with air-conditioning or mechanical ventilation equipment installed (eTable 1). Here, air-conditioning equipment is the entirety of equipment and attachments that purify intake air by means of air filters, electric dust collectors, or other devices and provide the air by controlling the temperature, humidity, and air flow volume, while the mechanical ventilation equipment means equipment that purifies intake air and provides the air by controlling the air flow volume. The CO₂ content tested with the detector tube method should be 1,000 ppm or less for both. In order to satisfy this requirement, 30 m³ of air should be ventilated in an hour per person present in the space.

It has repeatedly been stressed widely that for preventing coronavirus disease 2019 (COVID-19) clusters, avoiding the three C's, which are closed spaces with poor ventilation, crowded places with many people, and close contact for conversation, is important. Concerning closed space, the COVID-19 Response Headquarters of the Health, Labour and Welfare Ministry has determined that commercial facilities and other similar buildings with a great number of users that conform to the standards of air quality control stipulated in the Building Management Law are in compliance with the required ventilation volume, thus not falling into the poor ventilation category. Business operators of commercial or other facilities are recommended to implement the following ventilation methods. For industrial ventilation systems (air-conditioning or mechanical ventilation): (a) in the case of a specified building referred to in the Building Management Law, fulfillment of the standards of air quality control stipulated in the Building Management Law should be verified, and, if not fulfilled, maintenance measures should be properly implemented, including cleaning or adjusting ventilation equipment; (b) if not for a specified building, the fulfillment of required ventilation volume based on the Building Management Law (hourly 30 m³ per person) should be verified, and, if not fulfilled, the number of persons present in each room should be decreased to secure the required ventilation volume. For opening of windows: (a) windows should be fully opened for a few minutes at least once every 30 minutes; and (b) to generate air flow, windows should be opened on two different walls, if possible.

The measurement of air quality stipulated in the Building Management Law is to evaluate the ventilation status in the standard conditions of the subject building. In addition to ensuring sufficient ventilation in standard conditions, it is preferable for infection prevention to be able to obtain real-time information on ventilation progress when persons are working in the room. The CO₂ volume in respiration depends upon physical kinetic strength or the relative metabolic rate. The CO₂ exhalation data of

Japanese people has been made available in the Japanese Industrial Standards¹⁾ A series and the Society of Heating, Air-Conditioning Sanitary Engineers S²⁾ series standards. The CO₂ concentration in a perfectly unventilated room rises in line with the number of persons present in the room and their kinetic strength. Real time measurement of the CO₂ concentration will enable real time assessment of the ventilation status.

Objectives

This study consists of real-time measurement of CO₂ during a concert at an event hall, with the assistance of the concert organizer, to instantly visualize the measurement results. The objective is to examine the effect of the CO₂ visualization during a concert and to widely provide related effective knowledge for concert operations.

Methods

The outline of the concert

The concert was held on September 26, 2020 with bands of mainly young women singing. The doors opened at 2:00 p.m. and the concert started at 2:30 p.m. The musicians not on stage waited in a well-ventilated waiting room separate from the stage. The concert venue is a multi-purpose hall constructed in 1989, with a seating capacity of 188 (Figure 1). In actuality, however, the auditorium was prepared for only 91 seats, with each seat having the seats in front and back and on both sides vacant. This limitation conformed to the national government's policy then effective for stage performance events, which requested indoor venues to limit seats to a maximum of 50 percent of the nominal seating capacity. The audience was requested in advance to remain seated during the entire performance and not cheer for the musicians. They were also advised that if the CO₂ concentration exceeded 3,000 ppm, the concert would temporarily be suspended for forced ventilation operations. After the concert, the audience, musicians, and event organizing staff were requested to answer the online anonymous questionnaire concerning the visualization of the CO₂ concentration status. The concert hall data is in Table 1 below.

CO₂ concentration visualization

Since it was difficult and impractical to measure the individual CO₂ exposure, we set the CO₂ concentration measuring equipment near the center of the audience seats as a representative point (i.e., in the middle of the sixth row from the front). From 2:00 p.m., when the doors opened, the average of the CO₂ concentration every 10 seconds was shown to the concert audience on the monitor placed on the stage and the average of the CO₂ concentration every 60 seconds was recorded (Figure 2). For the measurements, dedicated equipment was used,

Fig. 1. Sketch of concert venue (cross section and floor plan)

Table 1. Air conditioning equipment of concert venue

		Audience seat	Stage	Audience seat & stage
Floor space		195 m ²	122 m ²	317 m ²
Volume		1,167 m ³	608 m ³	1,775 m ³
Air conditioning function of hall at the time of new construction	Supply air volume	15,000 m ³ /hour	4,500 m ³ /hour	19,500 m ³ /hour
	Return air volume	10,100 m ³ /hour	2,750 m ³ /hour	12,850 m ³ /hour
	Outside air volume	4,900 m ³ /hour	1,750 m ³ /hour	6,650 m ³ /hour
Calculated ventilation rate				3.74/hour

Fig. 2. Image of stage and monitor from audience seat

which was specially devised by the University of Electro-Communications, Tokyo, using a non-dispersive infrared type CO₂ sensor SCD-30 made by Swiss Sensirion (Stäfa, Switzerland).

Ventilation simulation model

The Occupational Hygiene and Ergonomics Section of the Japan Society for Occupational Health has a Ventilation Simulator system on its website to easily estimate the ventilation of a room³⁾. The system will estimate the CO₂ concentration figure from the measurements of the subject room, number of persons present and their kinetic level, as well as the ventilation volume (e.g., nominal design value) of the ventilator, if there is a ventilator and the value is known (Figure 3).

C	Indoor CO ₂ concentration		ppm
G	Generated CO ₂ (total of occupants)	$n \times k \times 0.01794$	m ³ /h
Q	Ventilation volume		m ³ /h
V	Room volume		m ³
m	Ventilation rate		/h
t	Elapsed time	∞	hour
Ce	Expiratory CO ₂ concentration	46,000 (fixed value)	ppm
Co	Outside CO ₂ concentration	400 (fixed value)	ppm
n	Total number of occupants		—
R	Expiratory volume per person	0.39 (fixed value)	m ³ /h
k	Mean activity coefficient		—

Fig. 3. Elements of ventilation model

We assume a model case in which the persons present in the room are the only CO₂ generation source, and the CO₂ generated at a constant speed from the persons gets mixed completely with a certain amount of ventilated air. In this case, the situation is expressed in the following equation (1), where the CO₂ concentration in the room is (C), total volume of CO₂ generated from the persons present in the room (G), volume of ventilated air (Q), cubic measure of the room (V), time passed (t) and CO₂ in the outside air (Co):

$$CO_2 \text{ concentration in the room } (C) = \frac{G}{Q} \left(1 - e^{-\frac{Q}{V}t} \right) \times 10^6 + C_0 \quad (1)$$

Total generated CO₂ volume (G) is expressed in the following equation (2), where the CO₂ concentration in the exhalation is shown as (Ce), number of persons present (n), respiratory volume per person (R) and kinetic strength (average activity factor: k). Here, the kinetic strength (k) is shown as 1: value in standard condition, 2: very light movement, 3: light movement and 5: exercise (light to heavy), and the Ventilation Simulator can accept only integers, not decimals, for the (k) factor:

$$G = C_e \times n \times R \times k \times 10^{-6} = n \times k \times 0.01794 \quad (2)$$

Therefore, the CO₂ concentration in the room in a time-homogeneous condition ($t = \infty$) can be expressed as:

$$CO_2 \text{ concentration in the room } (C) = \left[\frac{G}{Q} \times 10^6 \right] + C_0 = \left[\frac{n \times k \times 0.01794}{Q} \times 10^6 \right] + 400 \quad (3)$$

The CO₂ concentration in the room (C) in a time-homogeneous condition can be defined with the number of

persons in the room, average kinetic factor and ventilation volume. The ventilation volume is the product of the cubic measure of the room (V) and ventilation times (m). Thus, the CO₂ concentration in the room (C) in a time-homogeneous condition is defined with the number of persons in the room, average kinetic factor, cubic measure of the room and ventilation times.

The CO₂ concentration at the concert hall was simulated using the equation (3) above.

Results

CO₂ concentration progress during the concert

There were 35 listeners in the audience. During the performance, they followed the points requested in advance — to remain seated and not shout. The ventilation conditions of the hall were considered to have remained favorable at all times during the show, with the average concentration being 505.6 ppm and the maximum value 575 ppm. The concentration remained under the 3,000-ppm benchmark for concert interruption and forced ventilation. Figure 4 shows the transition of 5-minute moving averages of measured CO₂ concentration values.

The questionnaire distributed after the show was answered by a total of 26 people, consisting of seven audience members, 11 musicians, and eight organizing staff.

1) Did you notice the real time indication of CO₂ concentration value in the hall? Yes: 100 percent, No: 0 percent

2) What did you think of the concentration figures shown during the performance (in relation to the sense of security the CO₂ concentration values provided)? Made me feel very secure: 57.7 percent; made me feel secure: 42.3 percent; felt nothing, made me feel worried and made me feel very worried: 0 percent

3) Do you think that CO₂ concentration values should be visualized in the future (referring to needs for visu-

Fig. 4. Transition of CO₂ concentration values during live performance

alization)? Want them to do it again very much: 53.8 percent; doing again is acceptable: 46.2 percent; cannot say either, better not to do it again, never do it again: 0 percent

The answers of all types of respondents generally affirmatively referred to the sense of security the CO₂ concentration visualization provides, suggesting the acceptability and utility of real-time CO₂ visualization.

Ventilation simulation by means of model system

The necessary data for the simulation model were input. The number of persons present in the room was set as 45, consisting of 35 audience members and 10 others. The average kinetic factor during the concert was set at either 1 or 2. If it is 1 (standard conditions, or general seated deskwork level), the simulated CO₂ concentration came up as 523 ppm. If it is 2 (very light movement, or the level of responding to frequent telephone calls, a meeting with active discussion, doing light stretching exercises or slow walking), the CO₂ level was calculated as 646 ppm. The simulation demonstrated that the CO₂ concentration would become a time-homogeneous condition by approximately 1 hour after the concert starts. These simulation results largely agreed with the actual measurement values.

Discussion

This study measured CO₂ concentration on a real-time basis during a concert and instantly indicated the measurement results on a display. The visualization benefited

the audience, enabling them to enjoy the concert with a sense of security given the scientifically acceptable measurement results. The audience would also understand the necessity for performance interruption and forced ventilation in the case of elevated CO₂. The musicians also benefited, as they could perform with a sense of security based on scientifically acceptable measurement results and use the shown concentration values to communicate with the audience. The concert organizer's benefited by decreased infection risks among the audience and the musicians via timely ventilation of the hall, reliable display of CO₂ measurements to the audience and musicians, and by learning to apply the visualization knowhow to concerts held elsewhere for the same effective infection response measures.

At the same time, avoiding the misunderstanding that effective infection prevention comes just from good ventilation is extremely important. COVID-19 infection is thought to spread through droplet, airborne (droplet nuclei), and close contact⁴. The droplet infection is the main infection route, occurring if droplets emitted when an infectious person coughs, sneezes, talks, or sings are either inhaled by or come in contact with the mouth or nose membrane of a closely situated person (within approximately 1.8 meters). Airborne (droplet nuclei) infection occurs when a person inhales very small or micro droplets or particles containing viruses. These small or micro droplets or particles may be suspended in the air for some minutes to some hours. Less frequent contact infection occurs when a person contacts something attached with the virus and then touches their mouth, nose, or eye. Among the three infection types,

ventilation proves to be effective prevention only of airborne (droplet nuclei) infection. In addition to ventilation, effective prevention means for airborne (droplet nuclei) infection include using large-sized air cleaners with high efficiency particulate air (HEPA) filters and wearing masks in the venue. Useful preventative measures for droplet infection are wearing masks at the hall, physical distancing of audience seats, and fans refraining from shouting, dancing, and cheering. Contact infection preventions include disinfection of hands with alcohol, regular cleaning and sterilization of objects people often touch, wearing gloves when selling products, and restraint from holding handshaking sessions with musicians. It seems important to take multiple and comprehensive countermeasures in consideration of concert event-specific infection routes for preventing COVID-19 clusters. The visualization of ventilation resultant CO₂ concentration is an effective preventative measure of airborne (droplet nuclei) infection.

The concert hall where we studied was a good indoor environment with a CO₂ concentration of less than 1,000 ppm. Although we were able to show that there was no significant difference between the measured and simulated results in a good indoor environment, whether the measured and simulated results are in agreement even in an indoor environment with much higher CO₂ concentration remains unclear. This is a limitation of this study.

We would like to propose indoor environment countermeasures for different estimated CO₂ concentration levels as shown in Table 2 for airborne (droplet nuclei) infection prevention at the concert. Since it is basically difficult to open windows and doors for ventilation during performance in concert halls, it is necessary to take possible measures in advance based on the simulated results. Measures include ventilation improvement, such as asking facilities to increase the introduction of outdoor air; increase air filtration; turn off demand-controlled ventilation controls; and use fans to increase the effectiveness

Table 2. Indoor environment countermeasures for different estimated CO₂ concentration levels aimed to prevent airborne (droplet nuclei) infection at the concert

Estimated CO ₂ concentration, ppm	Measures in advance	Visualization of CO ₂ concentration
Less than 1,000 (favorable ventilation)		If possible
1,000 to less than 1,500 (fairly good ventilation)	Ventilation improvement ☐ ask facility to increase the introduction of outdoor air ☐ ask facility to increase air filtration ☐ ask facility to turn off demand-controlled ventilation controls ☐ use fans to increase the effectiveness of open doors and windows (to the extent that it does not affect staging) If the ventilation intervention in ventilation is difficult ☐ use portable high efficiency particulate air fan/filtration systems to enhance air cleaning ☐ use ultraviolet germicidal irradiation as a supplemental treatment to inactivate COVID-19 Secure enough ventilation rates per person and reduce CO ₂ generation ☐ limit the number of audiences in the concert venue ☐ ask audience to remain quiet in their seats ☐ ask audience to refrain from shouting	Recommended
1,500 to less than 2,500 (poor ventilation)		Strongly recommended
2,500 to less than 3,500 (very poor ventilation)		
3,500 or more (extremely poor ventilation)	Refrain from using the room	

COVID-19, coronavirus disease 2019.

of open doors and windows, to the extent that it does not affect staging. If the ventilation intervention in ventilation is difficult, use of portable HEPA fan/filtration systems to enhance air cleaning and use of ultraviolet germicidal irradiation as a supplemental treatment to inactivate COVID-19 are recommended⁵⁾. To secure high enough ventilation rates per person and reduce CO₂ generation, facilities could limit the number of audience members in the concert hall, ask audiences to remain quiet in their seats, and ask audiences to refrain from shouting³⁾. In concert halls, keeping windows and doors fully open at all times is probably not possible. Therefore, if CO₂ concentration is above 2,500 ppm, which is classified as very poor ventilation or extremely poor ventilation, it would be a good idea to “refrain from using the room” in accordance with the countermeasures indicated by the Occupational Hygiene & Ergonomics committee, the Japan Society for Occupational Health. In addition, visualization of CO₂ concentration in real time makes it possible to make a decision to prioritize ventilation over performance as an emergency measure. In case the estimated CO₂ concentration is less than 1,000 ppm (favorable ventilation), it is helpful to visualize CO₂ concentration for monitoring during regular times, if possible. In case the estimated CO₂ concentration is 1,000 to less than 1,500 ppm (fairly good ventilation), visualization is recommended to monitor for unusual occurrences, such as a sudden increase in CO₂ concentration. In case the estimated CO₂ concentration is 1,500 to less than 2,500 ppm (poor ventilation), visualization is strongly recommended in order not to delay appropriate ventilation. When trying to estimate the CO₂ concentration using the Ventilation Simulator system, it is recommendable for greater safety to input a higher kinetic factor even when the activities of persons present in the room are at a medium level.

Conclusion

This study consisted of real-time monitoring of CO₂ during a concert at an event hall in an attempt to instantly visualize the measurement results. The average CO₂ concentration during the concert was 505.6 ppm, with the maximum value being 575 ppm. These values were in line with the estimated values given by the Ventilation Simulator of the Occupational Hygiene and Ergonomics Section of the Japan Society for Occupational Health; thus, this Ventilation Simulator system was effective and useful. The CO₂ concentration visualization has the beneficial effects of providing a sense of security to the concert audience, musicians, and concert organizing staff. It is important to take multiple and comprehensive countermeasures given the concert event-specific infec-

tion routes for each COVID-19 infection type: droplets, airborne (droplet nuclei), and contact infections. The visualization of CO₂ concentration is one effective preventative measure for airborne (droplet nuclei) infection. To visualize the CO₂ concentration as needed based on prior estimation is strongly expected to become part of the standard operational procedure of concerts, as detailed in the indoor environment countermeasures for different estimated CO₂ concentration levels described above.

Author contributions

Y.I. and T.M. conceived the experiment and collected the data; H.K. and Y.I. analyzed the data; H.K. led the writing; Y.I., T.K. and T.M. provided feedback for each area of expertise.

Supplementary material

This article contains supplementary material (Appendix), which is available in the online version (doi: 10.1539/eohp.2021-0010-OA)

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