National Collaborating Centre for Environmental Health
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Indoor CO_2 Sensors for COVID-19 Risk Mitigation: Current Guidance and Limitations

Prepared by
Angela Eykelbosh

Primary inquiry: Information was requested regarding whether CO_2 monitoring could be implemented as a COVID-19 risk mitigation tool in restaurants. Building on a previous NCCEH document in which we explored some of the concerns around CO_2 monitoring as a public health tool, the scope was expanded to include all public health guidance regarding CO_2 monitoring by occupants to address ventilation adequacy during pandemic conditions.

Summary statement: CO_2 monitoring is an established tool to assess occupancy and ventilation requirements for indoor spaces, typically for the purposes of increasing energy efficiency. During the pandemic, it is critical that spaces are adequately ventilated for the number of occupants and type of activities, as one means to reduce risk of transmission. CO_2 monitoring can help to address ventilation inadequacy, provided that users are able to install, monitor, interpret, and react to these devices. However, indoor CO_2 levels should not be interpreted as a proxy for COVID-19 risk; SARS-CoV-2 transmission depends on multiple factors, of which ventilation is only one. There are numerous scenarios in which reliance on indoor CO_2 levels may cause occupants to under- or over-estimate the risk of transmission. In general, increasing CO_2 concentrations may indicate a lack of acceptable ventilation and an increase in COVID-19 risk if an infected person is nearby.

Background

SARS-CoV-2 transmission via aerosols – tiny droplets that do not settle due to gravity – is known to play some role in the pandemic.[1] It is unclear how often aerosol transmission occurs, but we know that we must act to mitigate it, through a combination of actions such as increasing fresh air supply (with natural or mechanical ventilation), cleaning indoor air with filters and germ-killing devices,[2] limiting the occupancy of spaces, and limiting activities that increase the emission of respiratory droplets. However, even when measures to improve ventilation are taken,[3] poor air mixing and low air flows can make it difficult to know whether ventilation is truly adequate for the number of people in a space and their activity levels, which change over time.

Monitoring CO_2 levels may useful in this regard because indoor CO_2 concentrations scale fairly reliably with the number of occupants and their activity level.[4] As the number of people in the room increases, or as their rates of respiration increase (for example, through exercise), CO_2 concentrations in the room will gradually climb. If CO_2 levels are increasing over time, it means that there is not enough fresh outdoor air getting into the room for the number of people present. It is necessary to manage CO_2 levels either by reducing occupancy or increasing the amount of outdoor air.

Despite the widespread use of CO_2 monitoring in building systems to save energy and reduce costs, the use of CO_2 monitoring as a public health tool has only recently gained attention.[5] However, indoor CO_2 monitoring carried out by non-expert occupants can be difficult to operationalize. Despite its seeming simplicity, some expertise is needed to interpret indoor CO_2 concentrations and what they mean for occupant health,[6] which may lead to unintended adverse effects if non-expert occupants are asked to monitor and react to these devices. CO_2 monitoring and enhanced ventilation are also limited because they only address the aerosol route of SARS-CoV-2 transmission, and are unlikely to decrease the risk of transmission during close interactions between one or more unmasked people. What role then could CO_2 monitoring play in reducing COVID-19 transmission in indoor spaces?

The aim of this field inquiry is to better understand the reasoning behind CO_2 monitoring and to communicate clearly about the potential benefits and limitations for COVID-19 risk mitigation. We used the following multi-pronged approach to address this inquiry:

- Expert consultation with specialists in environmental health, indoor air quality, and occupational health to clarify the challenges associated with CO_2 monitoring and suggest potential approaches;
- A rapid review of any pertinent academic or NCCEH resources;
- A grey literature search for existing guidelines or resources.

Expert consultation

Based on dialogue with environmental health experts within the NCCEH and partner agencies, several potential challenges related to CO_2 monitoring for COVID-19 risk mitigation were identified:

- The lack of any direct linkage between indoor CO_2 concentrations and COVID-19 transmission risk, and the high likelihood that CO_2 levels would be misinterpreted in this way;
- The variety of CO_2 monitoring products in the marketplace, their validity, and their averaging times;
- Poor general understanding of how CO_2 fluctuates over time as people enter and leave an enclosed area;
- The need to identify health-based thresholds for action and practical measures to reduce increasing CO_2 concentrations when detected;
- The likelihood that CO_2 monitoring would exacerbate risk perception and anxiety rather than alleviate it, whether due to differences in guideline values across jurisdictions, differences in CO_2 values in the same building, or differences in instrumentation;
- The need to devise more nuanced tools to understand the interrelationship between occupancy and fresh air requirements.

These concerns were used to guide a series of questions related to how CO_2 monitoring might be operationalized as a risk mitigation measure, supported by selected resources from the academic and grey literature.

Rapid review of academic and grey literature

A rapid literature review was conducted to identify resources related to indoor CO_2 monitoring and COVID-19 risk mitigation. Specifically, we sought public health guidance documents or intervention studies that included occupants actively using CO_2 monitoring to address indoor air quality (IAQ). EBSCOhost databases (including MEDLINE, CINAHL, Academic Search Complete, etc), Google, and Google Scholar were used to search for articles in English from 2011-2021. The search was conducted using variants and Boolean operator combinations related to indoor environments (room, office, restaurant, condo, etc), exposure to or monitoring of CO_2, the use of sensors and outcomes related to risk mitigation (transmission, infection, etc). Full search terms are available upon request.

Who is currently recommending CO_2 monitoring?

The literature search revealed a great deal of pre-pandemic information regarding the use of indoor CO_2 monitoring by experts to assess occupancy and ventilation. These studies were primarily related to energy savings and efficiency, although a growing body of literature has focused on CO_2 in schools with a comfort or health lens. However, there were very few guidance documents or studies that addressed CO_2 monitoring as a public health tool during the pandemic. Of the public health-oriented documents, several studies used CO_2 monitoring to assess or model infection risk (discussed previously[7]). Only a few documents (**Table 1**) advised on how to operationalize CO_2 monitoring for use **by occupants** as a risk reduction tool. No information was available regarding experiences or evaluation of occupants using CO_2 monitoring in this way.

Table 1. Public health guidance or other documents on the use of CO_2 monitoring to assess ventilation adequacy and reduce SARS-CoV-2 transmission risk.

Source	Document Type	Description	CO_2 Action Limit
American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE)	Guidance from professional organization	Typically recommends that indoor CO_2 levels are maintained within 500-700 ppm of ambient levels, as increases beyond this will lead to odour and comfort complaints amongst an unacceptable fraction of occupants.	1000-1200 ppm.
German Umweltbundesamt[8]	Guidance document	Recommends fixed or portable CO_2 "traffic lights" in schools to remind teachers and students	Lower green-yellow threshold set at 1000 ppm; yellow-

		to periodically open windows to facilitate classroom ventilation.	red threshold set at 2000 ppm.
Minnesota Department of Health[9]	Guidance document	Recommends CO_2 monitoring to assess ventilation adequacy in classrooms with high occupancy.	Keep rooms below 800 ppm.
Ottawa-Carleton District School Board[10]	Pilot study	Analyzed CO_2 data from an unspecified number of classrooms and found that they are able to maintain CO_2 levels below 800 ppm throughout the day with increased (maximal) ventilation.	Pre-pandemic set point was 1100 ppm.
Province of Quebec[11]	Pilot study	A CO_2 monitoring campaign was used to identify and remediate classrooms that exceed the guideline values.	Levels < 1500 ppm deemed acceptable.
Public Health Ontario[6]	Public health evidence brief	Notes that occupant-centred CO_2 monitoring is problematic because it requires expert knowledge.	None given.
Federation of European Heating Ventilation and Air Conditioning Associations (REHVA)[12]	Guidance from professional organization	Recommends use of CO_2 traffic lights in schools such that students and teachers will be aware of air quality, particularly during activities like singing, and open the windows.	Notes that green-yellow threshold should be reduced to 800 ppm for pandemic conditions.
UK Scientific Advisory Group for Emergency[13]	Public health guidance document	Supports the notion of using CO_2 monitors to identify poorly ventilated spaces and prioritize them for remediation. Notes that low CO_2 levels do not necessarily indicate sufficient ventilation in low-occupancy or high-volume spaces. Rejects	Spaces with CO_2 levels >1500 ppm should be prioritized for remediation. Spaces with aerosol-generating activities should aim for 800 ppm CO_2.

		the notion that CO_2 can be used as a direct proxy of COVID-19 risk.	
US Centers for Disease Control and Prevention[14]	Public health guidance document	Supports using portable CO_2 sensors with a logging function to monitor indoor spaces.	A portable air cleaner should be considered for spaces that cannot be maintained below 800 ppm.
Washington State[15]	Public health guidance document	CO_2 monitoring required to ensure that "open air" eating places (i.e., patios or restaurants with large open windows) are truly open to the outdoors.	If seated occupants are exposed to > 450 ppm for 15 min, they must be moved to a better ventilated table.

What is an appropriate action limit for indoor CO_2?

Health Canada has recently adopted a long-term indoor exposure guideline of **1000 ppm CO_2** for residential and other settings,[4] which is consistent with the comfort-based threshold of 1000 ppm promoted by professional organizations such as ASHRAE and REHVA. The Health Canada guideline was based on a review of the existing epidemiological studies and controlled exposures, in which indoor CO_2 levels were associated with various non-specific respiratory and neurophysiological symptoms (e.g., headache, fatigue). These studies did not demonstrate a causal link between CO_2 and symptoms, but rather reflect that one or more factors related to poorly ventilated environments may be having adverse impacts on occupants.

However, the 1000 ppm guideline value and others noted in **Table 1 may not be suitable for pandemic conditions**. During pandemic conditions, we should seek to keep indoor air as close to "fresh" outdoor conditions as possible, where outdoor air generally has a CO_2 concentration < 450 ppm. When CO_2 levels are consistently increasing over time, this is a strong signal that ventilation is inadequate for the number of occupants and/or their activities. However, because of the need to heat or cool air to keep the indoors comfortable, 100% fresh air is not always possible and some amount of CO_2 buildup is unavoidable. Notably, the US CDC and REHVA have reduced their recommended indoor CO_2 levels to 800 ppm during pandemic conditions.[12,14]

How should occupants be using CO_2 monitors?

The objective of installing a CO_2 monitor is for occupants to observe changes in CO_2 levels and then take action. There are two approaches to doing this (**Table 2**):

Table 2. Threshold vs. trend-based approaches to occupant-centre CO_2 monitoring.

Approach	Description	Advantages	Disadvantages
Threshold-based	Select an appropriate action limit and instruct occupants to take action if they approach or surpass that limit.	Action limits are relatively easy to understand and some CO_2 monitors can be programmed to alarm when the action limit is passed, reducing the attention required.	Occupants will only take action when CO_2 levels are high, rather than acting to keep levels low.
Trend-based	Use the data logging feature to display a CO_2 curve. Occupants take action when the curve is trending upward, indicating not enough fresh air for current use.	Reacting to increasing levels keeps CO_2 as low as possible; this is more consistent with public health messaging than the use of an arbitrary threshold.	Must be monitored closely. Trends over time may be not be immediately apparent. Occupants entering/exiting will lead to large oscillations, which may lead to user frustration/distraction.

For both approaches, the actions necessary to reduce CO_2 levels are the same:

- Open windows and doors;
- Take periodic breaks in which occupants leave the room to air out the space;
- Reduce occupancy;
- Avoid high-intensity activities;

- Increase fresh air supply via the HVAC system;
- Keep ventilation system fans running during occupied periods, after hours, and on weekends;
- Install local exhaust, although increasing exhaust is not as effective as increasing fresh air supply.

There may be some cases in which it is not possible to increase ventilation or reduce occupancy to maintain levels as desired. In such cases, it may be worthwhile to consider whether the activity can be moved to a different space or outdoors.

If it is not possible to move to a different space, a portable air cleaner may be useful.[2] Portable air cleaners do not add fresh air to a space or reduce the concentration of CO_2. However, if CO_2 levels indicate that ventilation is inadequate, then the people within that space may be at greater risk of infection if a sick person enters the space. Air cleaners can reduce the concentration of aerosols, but their effectiveness depends on positioning and other factors.[16,17] Occupants may not be aware if their air cleaner is not functioning as expected, so moving to a better ventilated space is preferable.

What types of CO_2 sensors are available?

There are various types of CO_2 monitors in the marketplace, but the simplist and most common technology is the non-dispersive infrared (NDIR) sensor. These sensors estimate the amount of CO_2 present by measuring how much light is absorbed across specific wavelengths. Because CO_2 absorbs light at specific wavelengths, there is minimal interference from other gases present, although humidity and temperature can affect the readout.

Numerous NDIR-CO_2 sensors are available. Accuracy ranges widely and price is not always an indicator of quality. Although there are many options, the following are some useful functions to look for:

- **The monitor has an appropriate range.** In most indoor spaces, CO_2 levels will range between outdoor concentrations (< 450 ppm) and about 3000 ppm (a stuffy indoor environment). In contrast, some CO_2 sensors are intended to function as personal safety devices in occupational settings with potentially very high exposures (up to 50,000 ppm); these devices should not be used for typical indoor environments.

- **CO_2 data are averaged over time**. Some CO_2 sensors provide a real-time point estimate of CO_2 concentration that can fluctuate wildly as air moves around. To smooth out some of the "noise," it can be useful to have a CO_2 monitor that displays CO_2 concentrations averaged over a set period of time. Averaging periods of 5-15 minutes are ideal for providing useful information without random fluctuations.
- **The monitor has a datalogging function**. Many typical indoor air quality monitors will continuously datalog temperature, relative humidity and CO_2 over adjustable time periods. The data can be downloaded to a computer or mobile device and graphed to show how CO_2 concentrations change during the course of the day or with varying occupancy.
- **The monitor shows trends over time**. Because many sensors show point estimates, and can fluctuate wildly, it is preferable for the CO_2 monitor to have a function that displays trends over time, either as a CO_2 curve or as an arrow indicator. If ventilation in the space is adequate, CO_2 concentrations should stay more or less steady throughout the day. However, if CO_2 levels are trending upward, this means that CO_2 is accumulating and the fresh air exchange is not adequate.
- **The monitor comes with adequate instruction.** Depending on the type of monitor purchased, the device may require maintenance and calibration to ensure accurate results over time.

Where do I put the monitor in the occupied room?

Properly locating the monitor is critical to accurately reflecting CO_2 concentrations. The sensor should be placed in a location with unobstructed air flow, but not in a location where it will be directly affected by windows, a ventilation system, or concentrated plumes of exhaled air. Ideally, sensors should be installed at a height relatively level with the height of occupants, between 0.5 m and 2 m above the floor. The following locations should be **avoided**:

- At or near a window;
- Near an air supply for a mechanical ventilation system;
- Within 2 m of any human occupant;
- Within 2 m of any open flame, such as a fireplace.

What are the limitations of CO_2 monitoring and increasing ventilation?

The resources reviewed here identified numerous limitations to the use of CO_2 monitoring to assess ventilation when used by non-expert occupants:

- It can be difficult to collect accurate data in poorly mixed spaces, especially when occupancy is low, or the interior air volume is large.[13] Low CO_2 levels measured in such spaces may not reflect conditions throughout the space. It may be necessary to have more than one monitor or relocate a single monitor multiple times, to cover the entire space.
- Although ventilation can help to reduce exposure to the smallest respiratory particles present throughout the room, **ventilation does not mitigate risk of transmission due to close contact with an infected person**. Ventilation does not act fast enough to interrupt the rapid exchange of respiratory particles during a face-to-face interaction.
- Ventilation also does not prevent larger particles from settling on surfaces, where they may contribute to potential fomite transmission.[18]
- As such, CO_2 monitoring and ventilation **do not replace any of the other necessary public health measures**, such as distancing, masking, surface cleaning, hand hygiene, etc.
- CO_2 monitoring does not replace the expertise of an HVAC professional; HVAC systems must be maintained and assessed periodically to ensure that they are working as designed.

What are the risks of using CO_2 sensors?

The two key risks of CO_2 monitoring as a COVID-19 risk mitigation tool are technological dependency (discussed previously[7]) and misinterpretation. CO_2 levels are easily misinterpreted as COVID-19 risk and may generate confusion and IAQ complaints if their uses and limitations are not clearly communicated. To facilitate communication, the following FAQs were devised:

- ### Does a high CO_2 level mean that COVID risk is high?

  No. Being exposed to high CO_2 levels does not mean you will contract COVID-19, and having low CO_2 levels does not mean that you cannot contract COVID-19.

  Although CO_2 has been proposed a proxy for COVID-19 risk,[19] the **readout on a CO_2 sensor is not a direct indicator of COVID-19 risk**.[13] The risk of COVID-19 transmission is based on numerous individual, environmental, and epidemiological factors[20] that vary independently of CO_2 fluctuations. For example, transmission risk varies with factors such as community transmission rates, which affect the probability that one or more infected people may be in the room. In addition, strategies such as air filtration and masking reduce COVID-19 risk, but do not affect CO_2 levels. The most important factors in transmission are the proximity and duration of contact,[20] as these factors increase an individual's exposure to respiratory droplets of all sizes. For this reason, **close interactions with others will remain the most important determinant of COVID-19 risk.**

If CO_2 levels in the space are trending upward, take action to reduce them – but high CO_2 does not indicate that you will contract COVID-19. Similarly, indoor CO_2 levels may be low, but risk of transmission is high if distancing and masking are not observed.

- **Are there other long-term health consequences of indoor CO_2 exposure?**

No. There are no long-term health consequences of being exposed to CO_2 at levels that are typically encountered in a non-industrial workplace or residence.
Although some research has found that CO_2 levels greater than 1000 ppm may be linked to poor cognitive performance, headaches, or other symptoms,[4] many other similar studies have not demonstrated these effects.[21] If any such effects do occur, they are reversible with removal to fresh air. Prolonged exposure to CO_2 levels greater than approximately 6000 ppm, which are rarely encountered in non-industrial settings, may elicit more serious effects, such as fatigue, visual impairment, and cardiovascular effects,[4] but these are again reversible with removal to fresh air.

- **Can we reduce ventilation if CO_2 levels can be maintained below 1000 ppm?**

In some facilities, CO_2 monitoring is used to estimate occupancy, which in turn is used to reduce outdoor air intake if/when occupancy is low. This is known as demand control ventilation and in non-pandemic conditions can be a useful energy-saving feature. However, under pandemic conditions, facilities should strive to keep the air as fresh as possible. Demand control ventilation should be disabled, and the aim should be to maintain CO_2 concentrations as close to outdoor levels as possible (< 450 ppm) while maintaining human comfort.

Summary

Throughout the pandemic, building managers and the public have been asked to ventilate their spaces adequately through HVAC adjustments, opening windows, installing local exhaust, etc. Without the assistance of an HVAC professional, it can be very difficult for building occupants to know whether ventilation objectives have been met. CO_2 monitoring is attractive in this sense: monitors are inexpensive and widely available, and they makes indoor air quality visible, which can help to identify poorly ventilated spaces for remediation.

However, the variety in quality and functionality of sensors, the need to install and operate them correctly, and the tendency to misinterpret CO_2 levels as COVID-19 risk means that this strategy must be considered carefully before implementation. Care must be taken to communicate very clearly around the proper use and limitations of this tool, and to emphasize that CO_2 monitoring and ventilation are part of a larger suite of public health tools to reduce transmission risk.

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655 W. 12th Ave., Vancouver, BC, V5Z 4R4
contact@ncceh.ca | www.ncceh.ca