Guide for ventilation towards healthy classrooms

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Authors of this report are members of INDAIRPOLLNET (INDoor AIR POLLution NETwork), a network of ~200 scientists from 36 countries, mainly around Europe. INDAIRPOLLNET aims to significantly advance the field of indoor air pollution science, to highlight future research areas, and to bridge the gap between research and business to identify appropriate mitigation strategies that optimise indoor air quality. This report will provide guidance to schools around Europe (and beyond) on best practice around ventilating their school buildings to minimise exposure to COVID-19 indoors. It aims to enable school managers to understand how the virus can accumulate and be transmitted in school buildings, and also suggests practical measures for reducing the viral load and hence transmission between occupants of school buildings.

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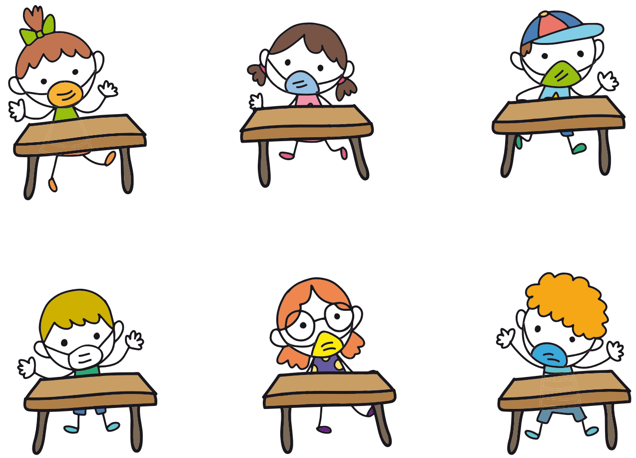
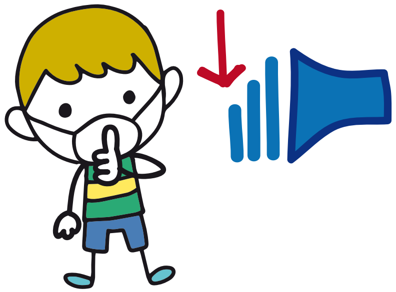
Summary

Outdoors
preferable to indoors



Reduce the number of students per classroom

Maintain a safe distance between students

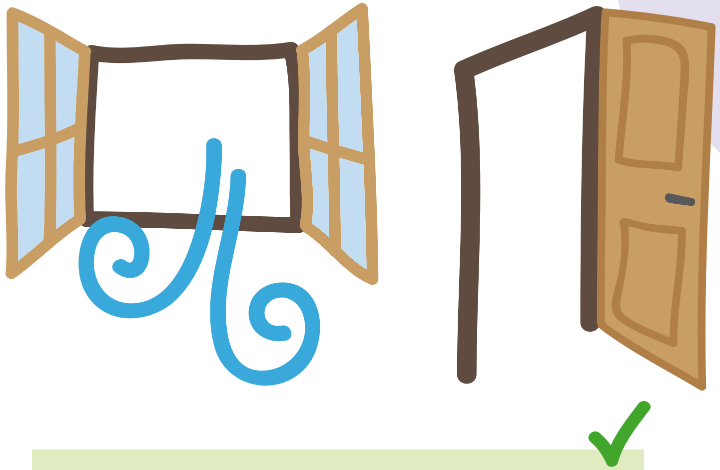


Silence or speaking quietly

Use a well-fitted mask

Summary

Reduce time indoors



Ensure sufficient ventilation

Provide air cleaning

Monitor CO2 levels

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About this guide on healthy indoor air in classrooms

- This guide is intended as a tool to reduce the potential spread of the SARS-CoV-2 virus through aerosol transmission. Strategies and possible solutions for ventilation in classrooms are provided, alongside tools to evaluate the implemented ventilation strategies.

- This guide has two parts. Part I focuses on how to maintain healthy indoor air in classrooms to reduce the risk of transmission of SARS-CoV-2 via aerosols, including ventilation and air cleaning, and how to check if the ventilation is sufficient to reduce risk using CO_2 as a tracer. Part II focuses on simulations of risk of infection under different scenarios (tackled in Part I) in a classroom.

- This guide is based on the Harvard University Guide (https://schools.forhealth.org) and other experimental studies on ventilation and filtration, as well as on modelling work by SCOEH (*https://scoeh.ch*).

- The guide can be applied to other types of indoor spaces, such as offices or other public buildings, though some adjustments may be needed for physical characteristics (e.g. area and volume).

- The use of masks, maintaining physical distance, and upholding hygiene measures, as recommended by governments and health experts, must be adhered to in conjunction with the strategies described here.

- The measures described here aim to reduce the risk of contagion, but they do not eliminate the risk entirely.

This guide should not replace the professional service provided by ventilation and air cleaning specialists. Individual spaces may require specific solutions and complex calculations that may need to be performed by technical specialists and professionals.

NEED-TO-KNOW INFORMATION

Need-to-know information

▸ The **risk of transmission** of SARS-CoV-2 is **greater in indoor areas** than in outdoor areas. Performing activities outdoors is always preferred where and whenever possible.

▸ Tiny particles held in suspension in the air, known as aerosols, emitted by an infected person can carry and transmit the virus. These aerosols can accumulate in poorly ventilated indoor spaces, and increase exposure to these aerosols, which can result in infection. **Reducing the emission of and exposure to these aerosols will reduce the risk of infection.**

▸ How much virus accumulates in the air can be estimated with an Indoor Scenario Simulator. Factors that affect are: room size and ventilation, activity of infectious person (talking, shouting, physical activity), type of masks worn by the infectious and the other people in the room.

▸ The emission of virus-carrying aerosols can be decreased by:

- Reducing the number of people in shared indoor spaces
- Wearing a well-fitted mask made of aerosol-filtering material
- Speaking quietly or maintaining silence (speaking loudly or shouting can increase the emission of aerosols by a factor of 30 to 50)
- Physical activity only in well-ventilated large halls or outdoors (increased physical activity increases emissions)

▸ The exposure to virus-carrying aerosols can be reduced by:

- Using a well-fitted mask, even while alone in a room that has been recently occupied by others
- Reducing the time for potential exposure
- Increasing the physical distance between individuals
- Ventilation or air cleaning to reduce the concentration of or eliminate the virus-carrying aerosols in the air

Ventilation & Air Cleaning

- **Ventilation** involves the **continuous replacement of potentially virus-contaminated indoor air with virus-uncontaminated outdoor air**. Note that using a fan in an enclosed indoor environment simply recirculates potentially virus-contaminated air in the enclosed space. Therefore, fans are not considered equivalent to ventilation systems that replace indoor air with outdoor air.

- When using **fans** at doors or windows to help replace air, **point them to the outside** so that air is exhausted from the room rather than blown into the room. Otherwise there is a risk that large droplets and aerosols (carrying viruses) are moved from one person to another.

- **Air cleaning** consists of the **removal from the air of suspended particulates** that potentially carry the virus. Filtration is the simplest and most effective method of air cleaning.

- The ventilation is defined parametrically as **Air Change Rate (ACR)** with its unit **air changes per hour (h^{-1})**. For instance, an ACR of 1 h^{-1} (1 air change per hour) means that there is an hourly flow of outdoor air equal to the volume of the indoor space. Due to the continuous mixing of outdoor and indoor air, an ACR= 1 h^{-1} results in a 63% replacement of indoor air with outdoor air in one hour. For ACR= 2 h^{-1}, 86% of the indoor air is replaced, and for ACR= 3 h^{-1}, 95% of the indoor air is replaced in one hour.

- The ventilation rate needed to reduce the risk of infection depends on the volume of air in the room, the number and age of the occupants, their activities, the case incidence in the region, and the risk level deemed acceptable. The Harvard Guide recommends **5-6 air changes per hour** in classrooms of 100 m^2 with 25 students of 5-8 years of age. The Harvard Guide has established the following classification:

ACR (h^{-1}) Ventilation

6	5-6	4-5	4-3	<3
DESIRABLE	EXCELLENT	GOOD	MINIMAL	LOW

- The air change rate is related to the outdoor air flow as:

$$ACR = \frac{Outdoor\ air\ flow}{Volume\ of\ air\ in\ the\ room}$$

- Another way to measure the required ventilation is the volume of outside air entering per person per unit of time (flow per person).

- The equivalence between ACR and the flow of air per person is not always the same and may change for different room sizes and different occupancy density (m^2 per person). For occupancies of about 4 m^2/ person and normal ceiling height, an ACR of 5 h^{-1} corresponds to **14 litres per person per second**. Hence this value of flow of air per person is considered a reasonable value to reduce the risk of infection.

- The relation between these two parameters is described by:

$$ACR = \frac{Flow\ per\ person * Numer\ of\ people * 3600 * 0.001}{Volume\ of\ air\ in\ the\ room}$$

where

ACR is in h^{-1}
Flow per person is in litres per person per second
Number of people is the number of people in the room
Volume of air in the room is in m^3
3600 is a conversion factor for units of time
0.001 is a conversion factor for units of volume

- Ventilation and occupancy may be adjusted according to the risk deemed acceptable. Zero risk of transmission is not possible—**however, higher ventilation lowers the risk of infection**.

- Ventilation in an indoor space can be approximately measured by monitoring the levels of **CO_2**. The concentration of CO_2 in outdoor air is approximately 420-480 ppm (parts per million). In occupied indoor spaces, CO_2 will be elevated relative to outdoor air due to the CO_2 exhaled by the occupants in the room. These CO_2 levels can be used to calculate air change rates in a given space under specific conditions (see further sections).

Risk of infection

- The **infection risk** depends on the **number of virus particles inhaled**. This depends on the number of viral particles in the air and how much of that air is inhaled. Adults have a higher respiration rate than small children, as do people exercising relative to those resting.

- To have viral particles in the air, a source (an infectious person), must be present in the room. **Not all infected persons emit the same number of viral particles**. About 1 in 10 infected people will emit sufficient viral particles to infect others via the air.

- One very infectious person (**superspreader**) in a room is **sufficient to infect everybody else in the room**, especially if the infected person is not wearing a mask.

- An infectious person emits the **highest number of viruses** from a few days before they start to have symptoms until a few days later. In this most infectious time they often have no fever. **Asymptomatic infected people also emit viral particles**.

- People with symptoms, namely those **coughing**, emit extremely high amounts of viral particles.

- An infectious person **speaking**, especially speaking or singing loudly, emits many **more viral particles than** a **silent** one.

- In most indoor situations, **wearing a well-fitted mask** helps in preventing infection, especially if both the emitter and the receiver wear a mask.

- **Good ventilation** and **avoiding lengthy gatherings in small rooms** are effective measures. However, they are often not sufficient as stand-alone solutions. It is advised to combine them with wearing masks.

Other considerations

- Where mechanical ventilation is not available, natural ventilation might be used. A compromise will have to be reached between thermal comfort during colder periods and the risk of infection. Warm, comfortable clothing can be worn indoors when windows are left open for ventilation to avoid the excessive use of heating.

- Natural ventilation may not always be a viable option under some meteorological conditions. In such cases, solutions should be implemented in advance of expected weather changes (such as before the onset of winter). Mechanical ventilation and/or air cleaning should be implemented before unfavourable weather conditions arrive.

- When using air cleaning units, they should be placed in an open space, that allows free air movement. Air cleaning systems with high efficiency filtration are recommended.

- Mechanical ventilation units require an initial hygienic inspection, recurrent hygiene inspections and an individual hazard assessment. Measurement techniques and tests in hygiene inspections comprise (i) hygiene tests of water in ventilation and air-conditioning units, (ii) microbiological testing of surfaces and (iii) air measurements.

- Keeping windows and doors open may create problems with noise. A compromise will have to be made between risks of infection and discomfort due to noise levels. For instance, controlling the noise levels in school hallways is preferable to closing the doors and windows.

- Keeping windows open may introduce higher levels of pollution from outdoor air, especially in areas with high outdoor air pollution. A compromise will have to be made between potential infection by Covid-19 and exposure to outdoor air pollution.

- CO_2 concentrations in occupied indoor spaces can increase rapidly due to respiration. This indicates inadequate ventilation and thus elevated levels of human bioeffluents (emissions). Replacing indoor air with outdoor air reduces the concentrations of these pollutants, which may cause building related symptoms (e.g. tiredness, sensory irritation, difficulty concentrating). Improved ventilation will improve the students' attention and performance.

- Low CO_2 may reflect low occupancy. Sufficient ventilation should be ensured even at relatively low CO_2 levels, since one infected person is sufficient to cause high viral levels in a room.

PART I:

VENTILATION & AIR CLEANING

Solution-finder flow chart

- Activities should be performed outdoors whenever possible, including meals.

- If an activity must be carried out indoors, it should be done in classrooms with adequate ventilation.

- Natural ventilation is better using cross-ventilation, i.e. windows and doors open on opposite sides of the room.

- If natural ventilation is not adequate, extra ventilation can generally be achieved using exhaust fans or individual outdoor air supply systems with sufficient airflows.

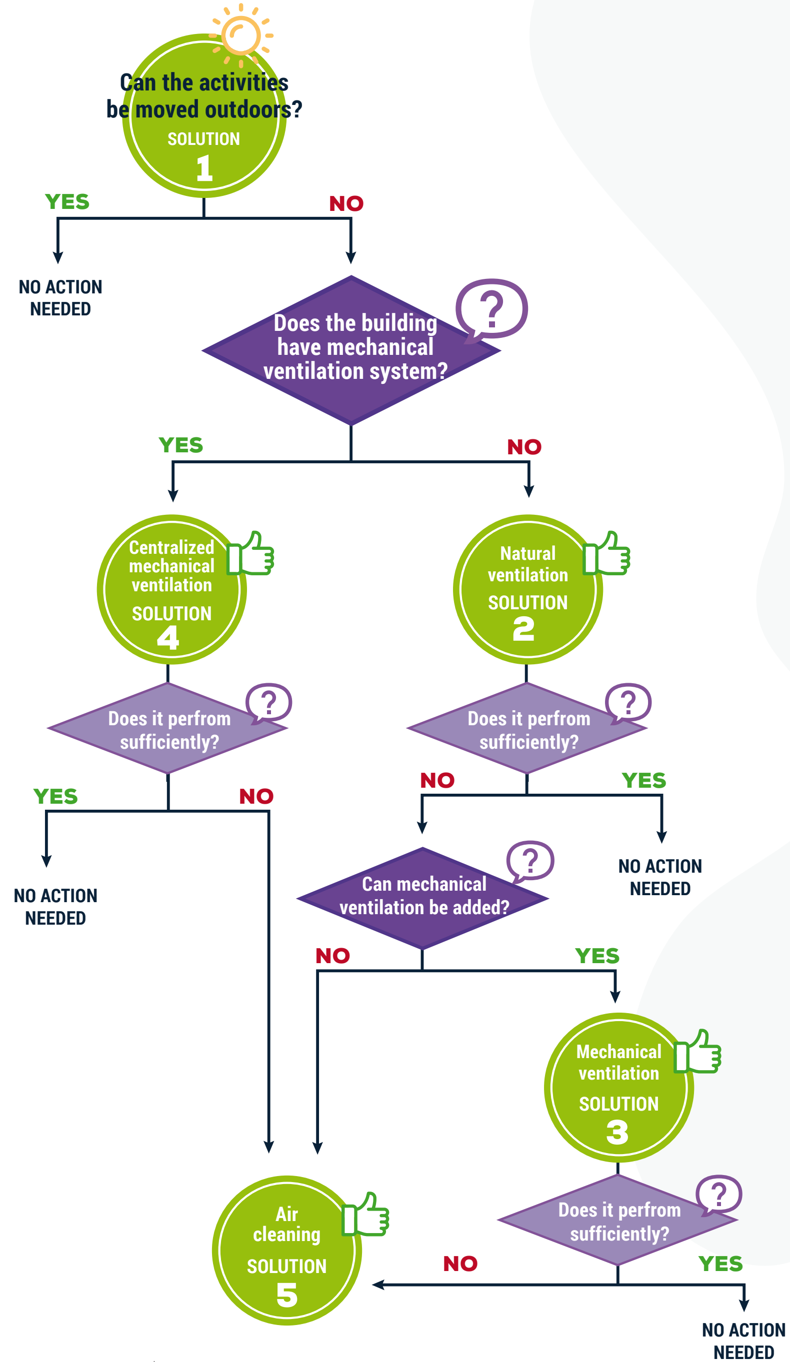
- Where centralised mechanical ventilation is available, the outdoor air flow should be increased while stopping or diminishing the air recirculation flow. The filters in the air recirculation flow should be upgraded to as efficient as possible.

- If none of the above options are available or sufficient, air should be cleaned using portable air cleaners equipped with HEPA filters.

- The optimum solution may be a combination of some of the above, such as for example a combination of natural ventilation and air cleaning.

- In the following sections, methods to evaluate the suitability of a given ventilation configuration are described.

- The correct use of masks, maintaining physical distance, and personal hygiene measures remain essential elements of all the solutions described here, including the solution to perform activities outdoors.



SOLUTIONS

Solution 1. Outdoors

Activities performed outdoors

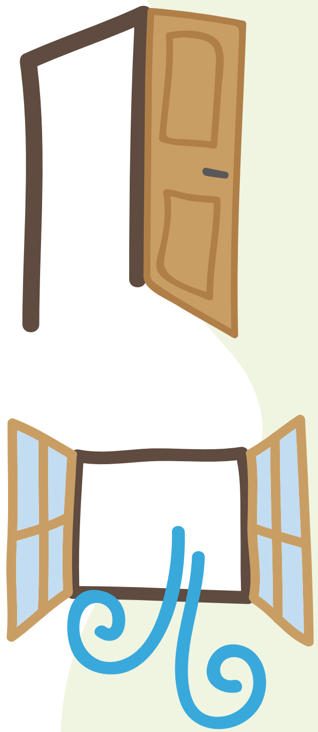
SOLUTION 1
OUTDOORS

- Outdoors, viral particles emitted by a potentially infectious person are naturally diluted and carried away from the vicinity of the source.

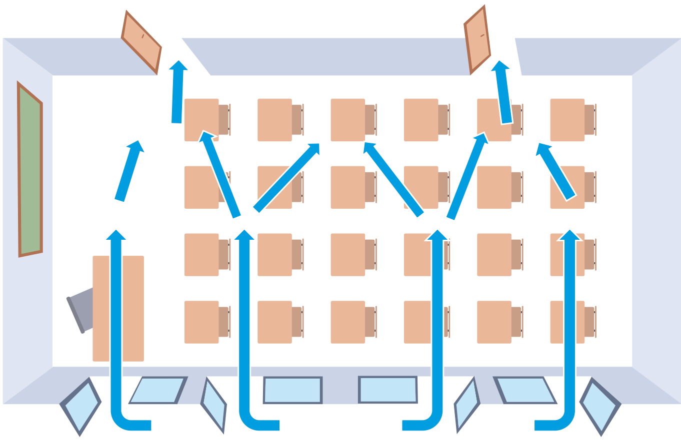
Solution 2. Natural ventilation

Indoors, where natural ventilation is sufficient (see further information on how this can be determined)

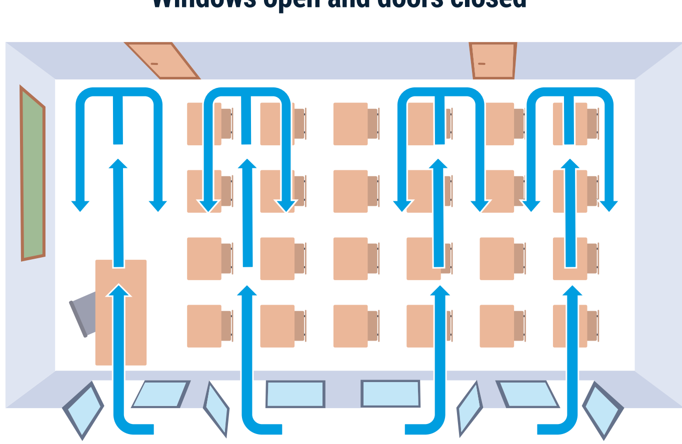
- This solution increases the outdoor air change rate (ACR) without using mechanical equipment, for example, by opening windows and doors to promote airflow.
- Cross-ventilation consists of opening windows and doors on opposite sides of a room. Cross-ventilation is more effective than opening windows and doors on the same side of a room and is therefore preferable. In most cases, sufficient ventilation cannot be achieved without cross-ventilation.
- Outdoor conditions affect the effectiveness of natural ventilation. The ventilation provided by a particular configuration of windows and doors may change with wind direction, speed and indoor/outdoor temperature differences.
- Different configurations of open windows and doors should be tested (see further information on how performing these tests).
- Natural ventilation can be enhanced by placing a fan facing an exterior window, with the airflow directed outdoors, so that the rate of extraction of indoor air is increased. This can technically also be considered single-room mechanical ventilation, and would therefore be similar to Solution 3.



Cross-ventilation

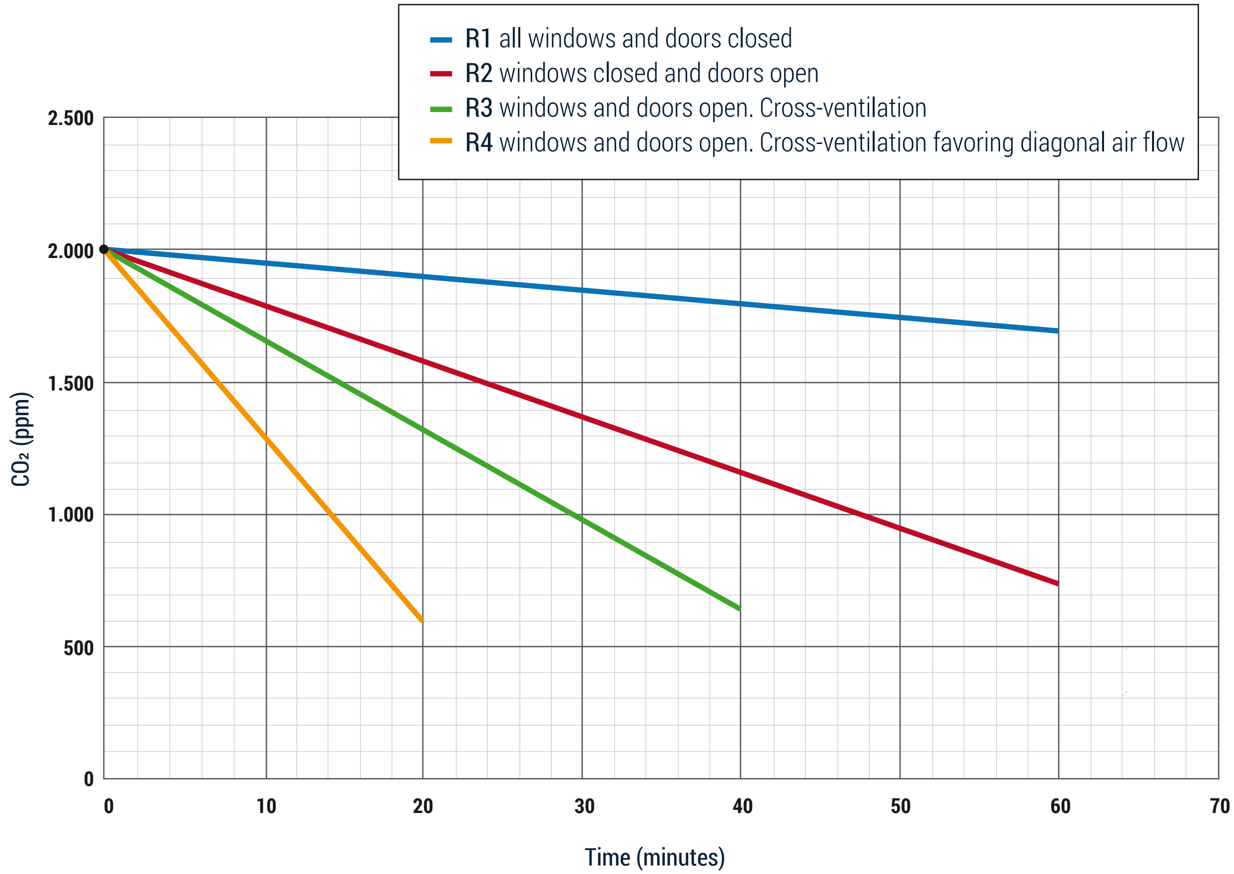


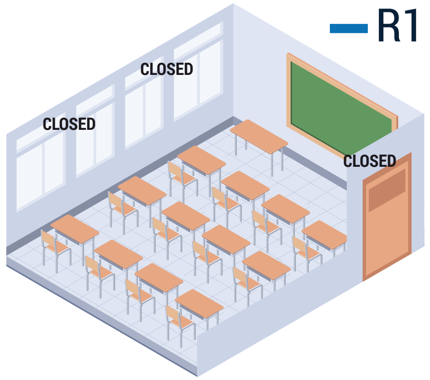
Windows open and doors closed

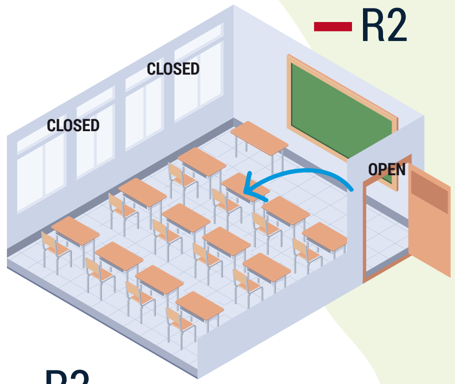


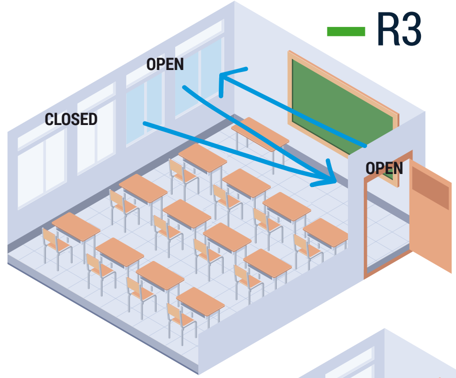
SOLUTION 2 NATURAL VENTILATION

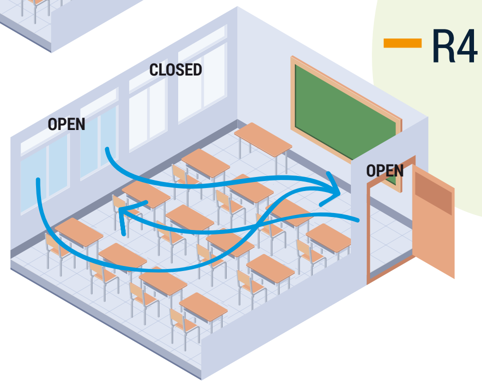
Variations in CO_2 concentrations indicating the rate of air change under different ventilation configurations







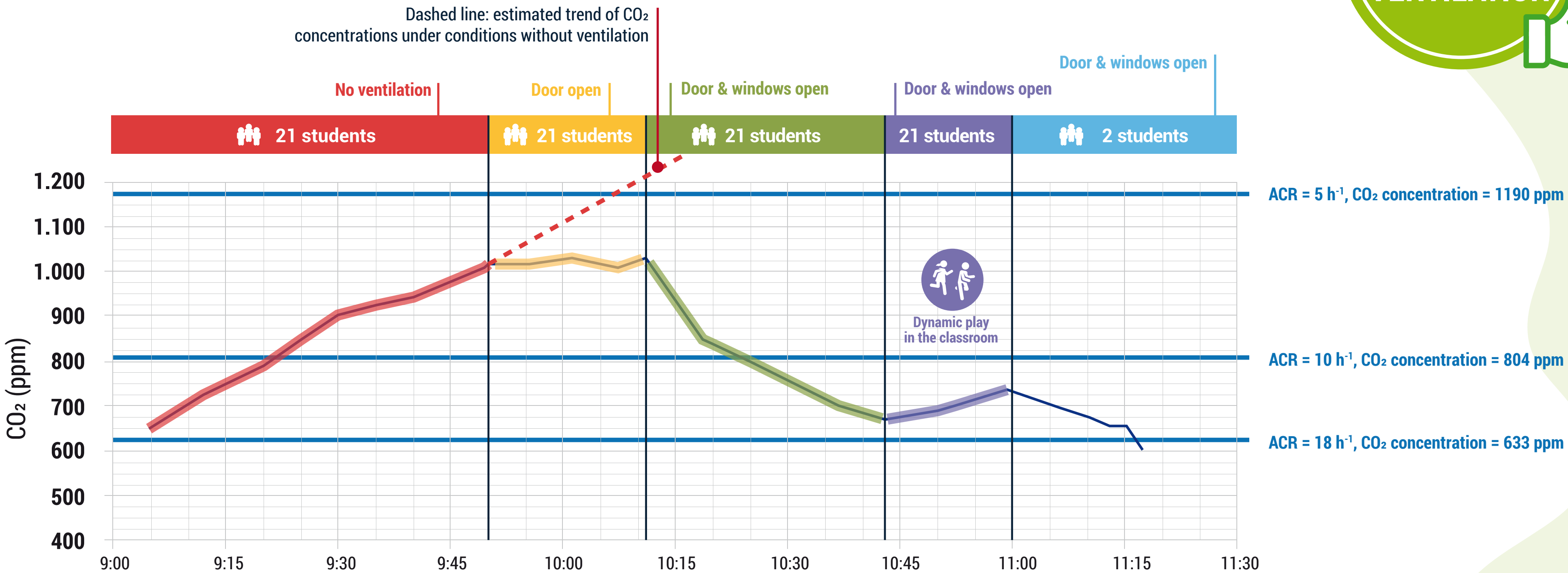




Example of natural ventilation

SOLUTION 2
NATURAL
VENTILATION

Variations in CO2 concentrations in a classroom under different ventilation configurations.



In this example, the classroom volume is 61 m³ and it is occupied by 21 infant students and one teacher. For this occupancy, more than 5 air changes per hour are recommended. In the adjoining graph, the variations in concentrations of CO2 in indoor air are shown under steady state conditions at 5, 10, and 18 air changes per hour (the last value is equivalent to airfow of 14 liters per person per second).

As this example demonstrates, CO2 concentrations increase over time in the absence of ventilation. Within 45 minutes, CO2 levels reach 1000 ppm. This increase is halted when the doors are opened. When both the windows and doors are opened in a cross-ventilation configuration, CO2 levels begin to decrease. The eventual stabilisation of the CO2 levels indicates that the CO2 concentration can be compared to the calculated target concentration in steady-state. As it is below 804 ppm, this means that 10 air changes per hour are reached.

(For details on these calculations, consult the methods at the end of Part I of this guide).

mimoCO₂ https://webmesura.org/mimoco2/

Solution 3. Single-room mechanical ventilation

Indoors, where natural ventilation is insufficient and single-room mechanical ventilation is available.

SOLUTION 3 SINGLE-ROOM MECHANICAL VENTILATION

- This solution consists of using mechanical methods to increase the exchange rate of indoor air with outdoor air.

- This solution can be implemented by introducing outdoor air into the room (supply ventilation), removing indoor air from the room (exhaust ventilation) or both.

- The air supply and exhaust point can be a window, or a specifically designated vent with a fan in the wall or ceiling.

- The necessary flow is calculated according to the required air change rate, taking into consideration that ventilation methods are cumulative:

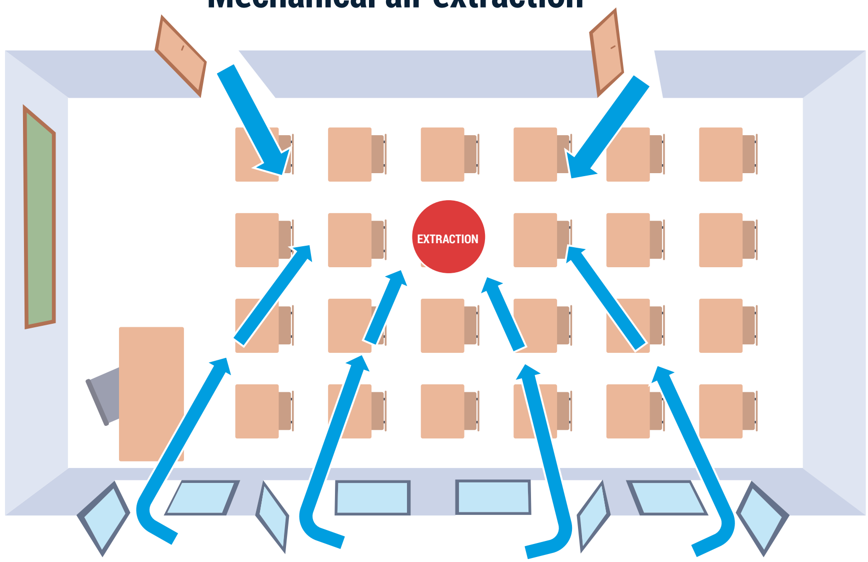
Target ACR = Total ACR = ACR (natural ventilation) + ACR (mechanical ventilation)

- The necessary flow will be:

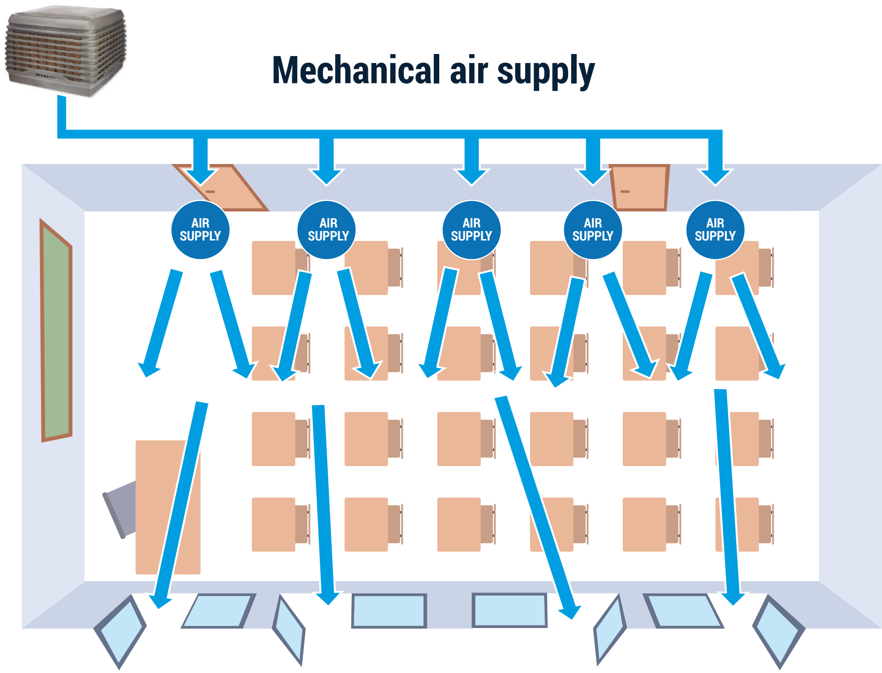
*Flow = ACR (mechanical ventilation) * Volume of air in the classroom*

- Some times the flow cannot be measured with this type of systems. In those cases, the assessment of the air change rate achieved must be done similarly to situations with natural ventilation.

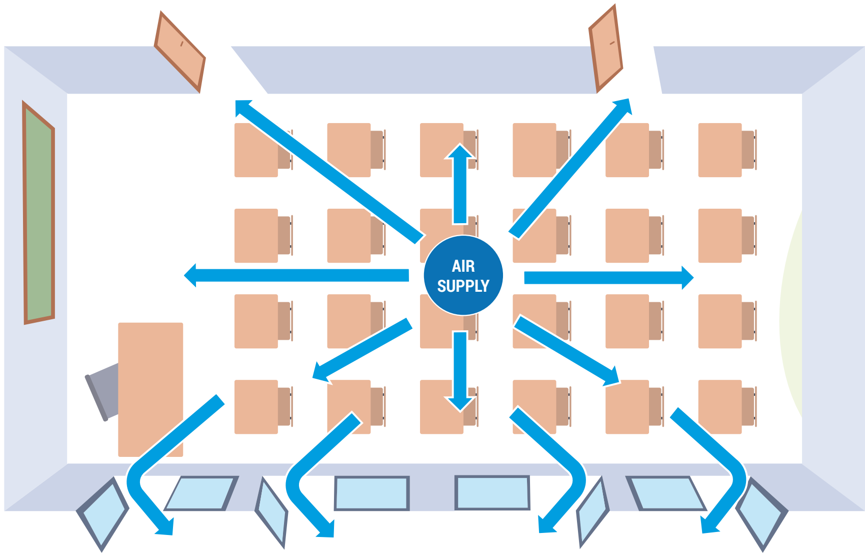
Mechanical air extraction



Mechanical air supply



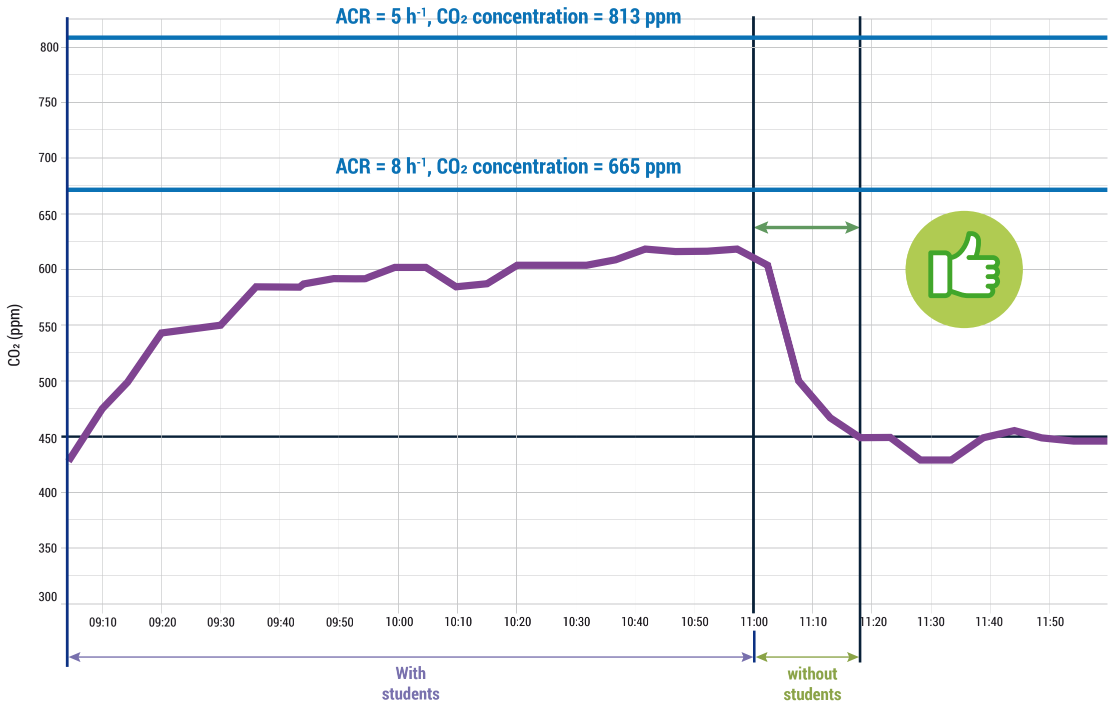
Mechanical air supply from the ceiling



Example of mechanical ventilation

SOLUTION 3 SINGLE-ROOM MECHANICAL VENTILATION

Variations in CO2 concentrations in a classroom, with and without students, equipped with single-room mechanical supply ventilation.



mimoCO₂ https://webmesura.org/mimoco2/

In this example, the classroom has a volume of 142 m³ and contains 21 students of 10 years of age and one teacher. With this occupancy, more than 5 air changes per hour are recommended. In the adjoining graph, the indoor steady-state CO2 concentrations corresponding to 5 and 8 air changes per hour are indicated (the latter value is equivalent to conditions for 14 liters per person per second).

In this example, mechanical ventilation is activated during the entire period, achieving sufficient air change rate, as reflected by the CO2 concentrations. The CO2 concentrations do not exceed levels corresponding to 8 air changes per hour.

When the students vacate the classroom, the CO2 concentrations rapidly decrease to background level.

(For details on these calculations, consult the methods at the end of Part I of this guide).

Solution 4. Centralised mechanical ventilation

SOLUTION 4 CENTRALISED MECHANICAL VENTILATION

Indoors, where centralised mechanical ventilation is available.

- Centralised ventilation systems provide ventilation for entire buildings to facilitate the exchange of indoor air with outdoor air. Such ventilation systems are typically used for air conditioning.

- Such systems should be configured to maximize the supply of outdoor air relative to the recirculated indoor air. The modification of existing configurations must be carried out by trained technical personnel.

- Recirculated indoor air can be filtered by introducing a suitable filtration system or upgrading the existing one. The filter used in the recirculation flow should have the maximum efficiency that the system is able to handle considering the limitations on pressure drop (energy use) and other system requirements. A minimum filter efficiency >50% for particles lower than 1 μm is recommended (EN ISO 16890; aproximatelly equivalent to F7 by the old EN779 standard). The flow of clean air provided by this system is calculated by multiplying the flow of the recirculated air by the efficiency of the filter in use.

*Flow of clean air from recirculation with filtration = Flow of air * Filter efficiency*

- The necessary flow is calculated according to the required air change rate, taking into consideration that ventilation rates are cumulative, i.e. when natural and mechanical ventilation are combined, the total ACR is cumulative; therefore, the ACR of natural ventilation is added to the ACR of the centralised mechanical ventilation. Nevetheless, natural ventilation can interact with the mechanical ventilation flows and result in a different combined ventilation.

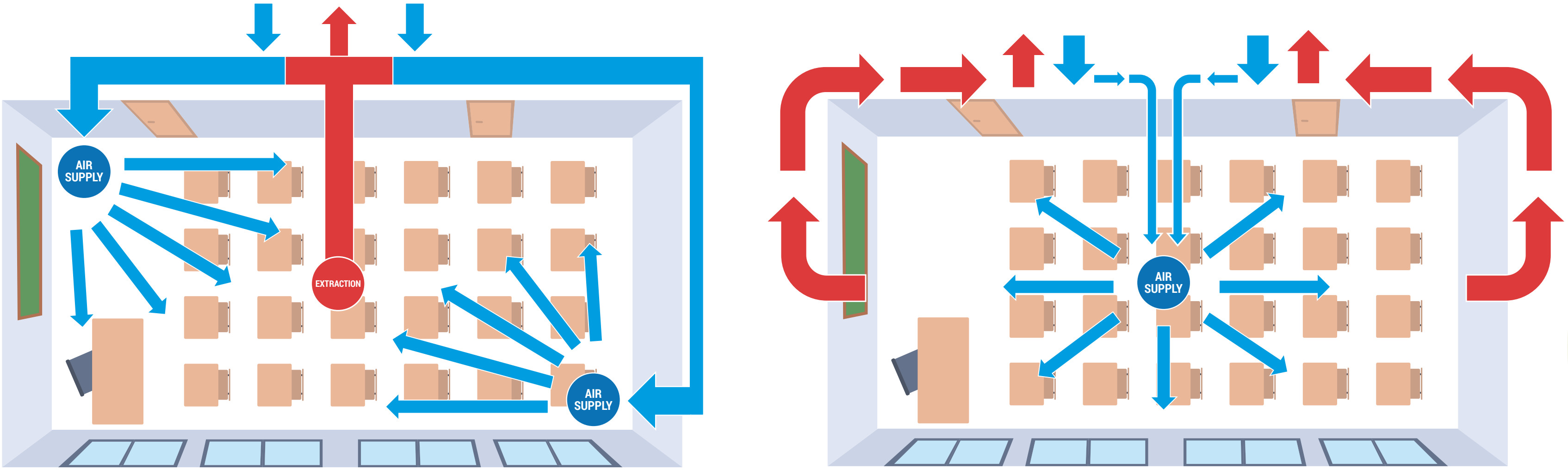
Target ACR = Total ACR = ACR (natural ventilation) + ACR (centralised mechanical ventilation)

- The theoretical required mechanical flow is given by:

*Flow = ACR (centralised mechanical ventilation) * Volume of air in the classroom*

- When the mechanical flow cannot be measured with this type of systems, and even if so, given that the natural ventilation can interfere with the flows, the assessment of the total air change rate achieved must be done similarly to situations with natural ventilation.

Centralised ventilated air fed into the classroom from the ceiling



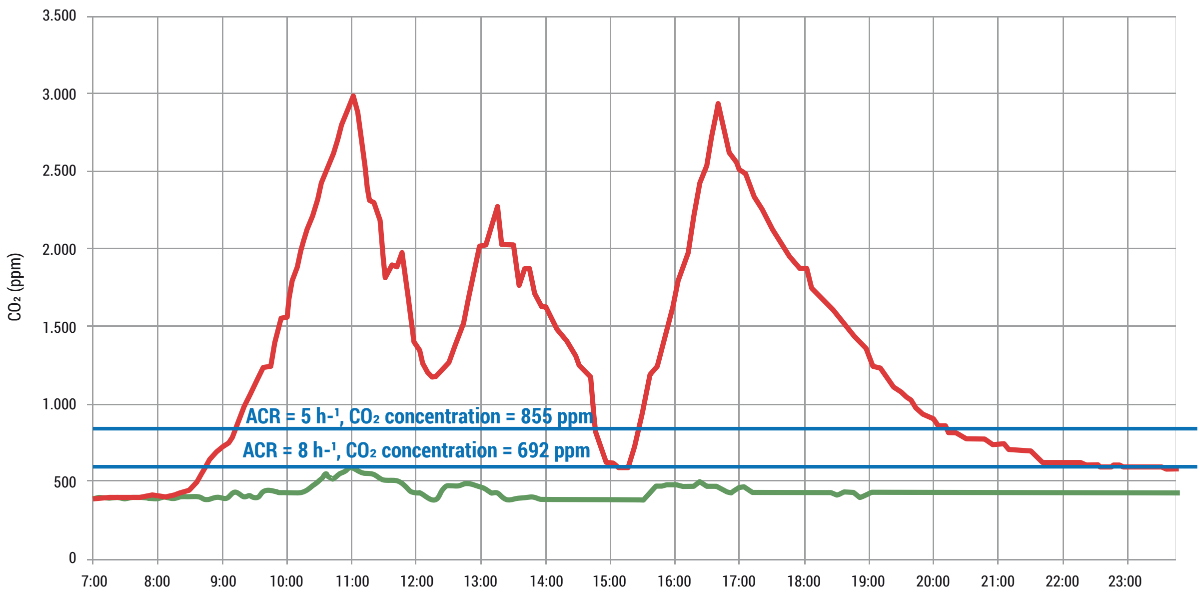
SOLUTION 4 CENTRALISED MECHANICAL VENTILATION

Example of centralised mechanical ventilation

Variation of CO_2 concentrations during a school day without (red) and with (green) centralised mechanical ventilation.

— **Red:** windows and doors closed (April 2015).

— **Green:** Mechanical ventilation (supply mechanical ventilation without recirculation (May 2019)).



mimoCO₂ *https://webmesura.org/mimoco2/*

In this example, the classroom has a volume of 148 m³ and contains 22 students of 14 years of age and one teacher. With this occupancy, more than 5 air changes per hour are recommended. In the adjoining graph, the indoor steady-state CO_2 concentrations corresponding to 5 and 8 air changes per hour are indicated (the latter value is equivalent to conditions for 14 liters per person per second).

In this example, mechanical ventilation is running continuously. The theoretical air change rate is 11 air changes per hour (based on the system flow).

(For details on these calculations, consult the methods at the end of Part I of this guide).

Solution 5. Air cleaning

Indoors, where natural or mechanical ventilation is not available or is insufficient .

SOLUTION 5
AIR
CLEANING

- In this solution, an air cleaner is installed to remove particles potentially carrying viral particles from indoor air.

- An air cleaner's effectiveness in reducing particles is defined by their *Clean Air Delivery Rate (CADR),* typically expressed in m^3 per hour.

- The air change rate equivalent to the air cleaner's CADR is:

  ACR(cleaning) = CADR / Volume of air in the classroom

- The total effect of ventilation and air cleaning on particle levels in the same space is:

  ACR(total) = ACR(ventilation) + ACR(cleaning)

- The required air cleaning (ACRcleaning) is calculated by:

  ACR(cleaning) = ACR(total) - ACR(ventilation)

- The required clean air flow, Clean Air Delivery Rate (CADR), is calculated by:

  *CADR= ACR(cleaning) * Volume of air in the classroom*

- More than one air cleaner can be used to achieve the necessary airflow.

- The air cleaner should be positioned in the centre of the classroom if possible while avoiding blowing air directly at the room's occupants.

- Filtration is the most effective system of air cleaning. Filtration consists of passing contaminated air through a filter, which traps particles in the air stream. HEPA (*High-Efficiency Particulate Air*) filters H13 (>99.95% efficiency) or higher are recommended (EN1822 standard).

- Ionizers or ozone generators are not recommended because they can produce uncontrolled reactions with other atmospheric components and form harmful contaminants. More information can be found in the EPA guide on indoor air cleaners (*https://www.epa.gov/indoor-air-quality-iaq/air-cleaners-and-air-filters-home*)

- Filters should be changed in accordance with the manufacturers' instructions.

Note: the equations used to calculate CADR and ACR(cleaning) are provided in the excel spreadsheet in the annex.

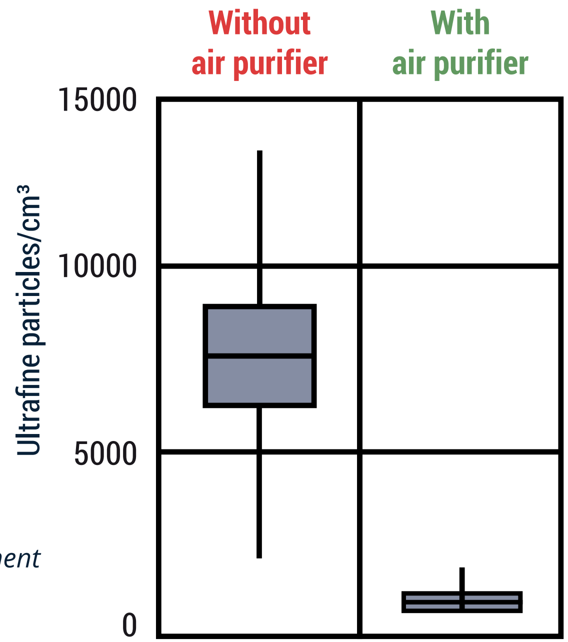
Example of air cleaning

Variations in the concentration of ultrafine particles in a school gymnasium occupied by students, with and without air cleaners with HEPA filters installed.

The SARS-CoV-2 can be carried in particles of different sizes, from ultrafine to coarse. Here the assessment of the air cleaner efficiency is done using ultrafine particles, and this implies that the efficiency for the whole range of sizes in which the virus can be present is equal or larger than that.

Red arrows: air cleaner

Pacitto et al., 2020 Science of the Total Environment



In this example, six air cleaners are installed, each with flow rates of 660 m³ per hour, in a school gymnasium of volume 430 m³ (150 m² * 2.9 m).

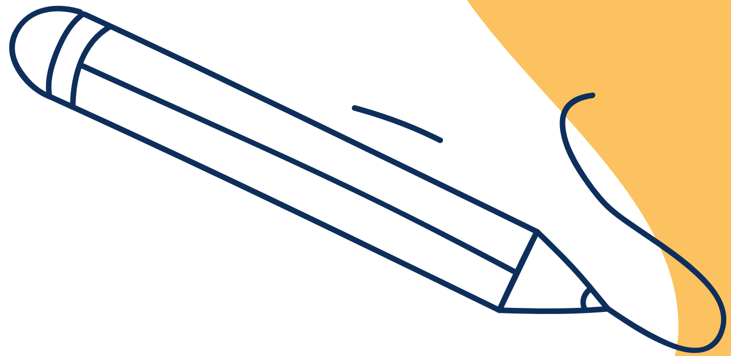
The total flow is 660*6 = 3960 m³/h.

The equivalent air change rate provided by the six air cleaners is given by:

ACR(cleaning) = 3960/430 = 9.2 air changes per hour.

A substantial decrease in the concentrations of potentially contaminated ultrafine particles in the indoor air is observed when the cleaner is used.

VERIFYING THE VENTILATION EFFICIENCY USING CO_2 SENSORS



Verifying the ventilation efficiency using CO_2 sensors

When an enclosed space is occupied by people, concentrations of exhaled CO_2 in indoor air can be used as indicator of ventilation.

There are two methods to measure ventilation, both based on the measurement of CO_2 in indoor air.

These methods are intended to quantitatively determine air change rate in classrooms following the established ventilation recommendations. With all data available the ventilation can be expressed as air change rate in air changes per hour (h^{-1}) or as air flow per person in litres of air per person per second.

Concentrations of CO_2 in ambient outdoor air are approximately 420-480 ppm, depending to the proximity to combustion sources.

Both methods consider the dilution effect of outdoor airflow only. If air cleaning is employed, its effect and that of ventilation are cumulative. For example, if ventilation provides an air change rate of 4 h^{-1}, and the air cleaner provides a CADR equivalent to 3 h^{-1}, the cumulative effect on removal of air pollutants is 7 h^{-1}.

Method 1. Determination of air change rate

This method directly measures the air change rate (ACR) in air changes per hour (ACH). This method requires the room to be unoccupied with no additional sources of CO_2. CO_2 concentrations are deliberately increased in the unoccupied room, and the rate of decrease in CO_2 concentrations is measured. The rate of the decrease can be used to calculate the air change rate..

- Measure the outdoor ambient CO_2 concentrations for at least five minutes before and after the experiment. The average measured CO_2 concentration represents the baseline ambient CO_2 levels.

- Place the CO_2 sensor in the classroom approximately one meter above the ground, and monitor the CO_2 concentration continuously.

- Increase the CO_2 concentration in the classroom (with all windows and doors closed) to approximately 2000 ppm by:
    - Having one or more individuals stay in the room (this can be a regular classroom session)
    - Using a source of CO_2 such as dry ice.

- When CO_2 reaches at least around 2000 ppm:
    - Remove the CO_2 source (such as the dry ice, if used)
    - Ensure every person vacates the classroom
    - Open the windows and doors according to the configuration being tested

- Allow the CO_2 concentrations in the classroom to reduce. Avoid changes to positions of doors and windows or ventilation system settings during this period.

- Excess CO_2 is defined as:

$$\text{Excess } CO_2 = \text{indoor } CO_2 \text{ concentration} - \text{outdoor } CO_2 \text{ concentration}$$

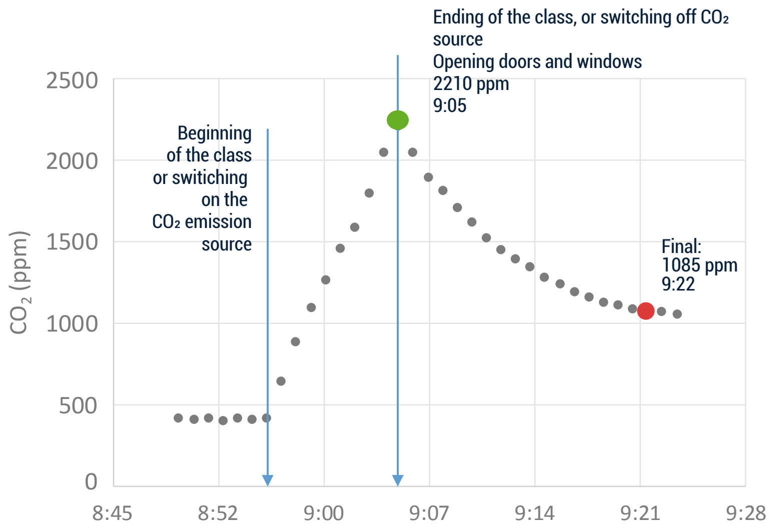
- The test ends when the excess CO_2 reaches 37% of the initial excess.

Example:

- Maximum initial indoor concentration is 2000 ppm
- Outdoor concentration is 420 ppm
- Initial excess CO_2 = 2000 - 420 = 1580 ppm
- Final excess CO_2 = 37% of the initial excess CO_2 = 1580 * 0.37 = 585 ppm
- Final indoor concentration = 420 + 585 = 1005 ppm

- Repeat the method for different window and door opening configurations.

Processing the data



- Download or take note of the measurement data recorded by the CO2 sensor. Every 1 minute or less should be recorded.

- Identify the moment when the windows and doors are open and the CO2 concentration begins to decrease. Ignore instances where the CO2 concentration oscillates around the same value and instead choose the point when CO2 clearly begins to reduce continuously. The **green point** in the adjoining graph indicates this concentration (C_{start}) and the time t_{start}.

- Identify the moment when the CO2 concentration reaches the final indoor concentration (as calculated previously). The **red point** in the adjoining graph indicates this concentration (C_{final}) and the time t_{final}.

- Calculate the average CO2 concentration in outdoor air measured with the sensor before and after the indoor tests ($C_{outdoor}$).

- Use the following equation to calculate the air change rate (ACR), where C is the concentration in ppm and t is the time in hours:

$$ACR = \frac{-1 * \ln\left(\frac{C_{final} - C_{outdoor}}{C_{start} - C_{outdoor}}\right)}{t_{final} - t_{start}}$$

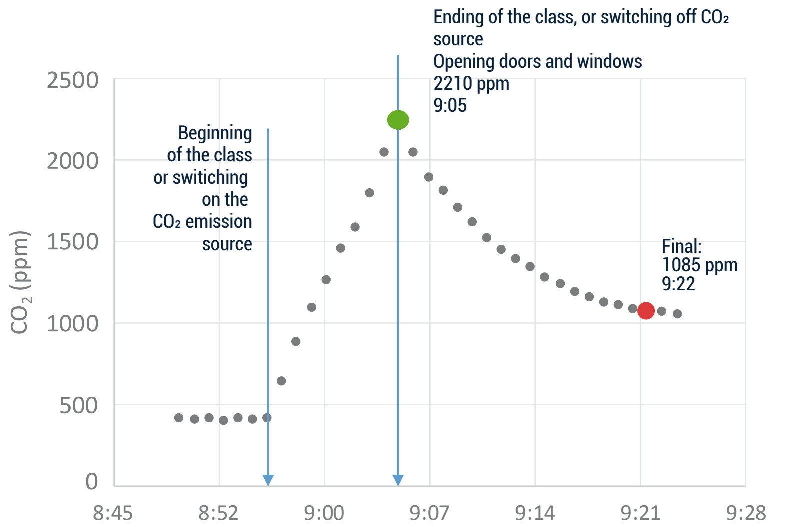
- Compare the obtained air change rate with the target value and modify settings as necessary before re-testing the ventilation conditions.

Note: these calculations can be made using the Excel spreadsheet provided in the annex of this guide.

Method 1 Example

- Point where CO2 concentrations begin to reduce, **C_{start} = 2210 ppm y t_{start} = 09:05**
- Point where CO2 concentrations stop decreasing, **C_{final}= 1085 ppm y t_{final}= 09:22**
- Outdoor concentration, $C_{outdoor}$ = 420 ppm
- Experiment time $t_{final} - t_{start}$ is 17 minutes. This is 17/60 = 0.2833 hours
- Calculate ACR as

$$ACR = \frac{-1 * \ln\left(\frac{1085 - 420}{2210 - 420}\right)}{0.2833} = \mathbf{3.5}$$



- Comparison of the achieved value (ACR = 3.5 h^{-1}) with the target value.

  Option 1. Take the desired ACR (target), e.g. 5 h^{-1}

  Option 2. Take as the target 14 litres per person per second and calculate the corresponding ACR. For example, 23 people in a classroom of area 70 m² and height 2.8 m height (70 * 2.8 = 196 m³) corresponds to:

  ACR = 14 litres per person per second * 23 people * 3600 seconds/hour * 0.001 m³/litre / 196 m³ = 5.9 h^{-1}

- At an ACR (target) = 5 h^{-1}, additional air change rate of 1.5 h^{-1} is required (5.0 - 3.5)

Using the 14 litres of air per person per second target, additional air change rate of 2.4 h^{-1} is required; 5.9 - 3.5).
The precautionary principle would imply to use the most restrictive value from the two above).

- Options:
  - Modify the window and/or door configurations in order to achieve the required ACR
  - Use additional mechanical ventilation to achieve the extra 1.5 h^{-1} needed. Required extra flow = 1.5 * 196 = 294 m³ per hour.
  - If the exact flow of the mechanical ventilation cannot be determined precisely, method 1 can be repeated with a new ventilation configuration (natural and mechanical) to determine the total achievable ACR.
  - Employ an air cleaner to provide the extra 1.5 h-¹ needed. The required clean air flow from the cleaner would be CADR = 1.5*196 = 294 m³ per hour.

Method 2. Determine the target steady-state CO_2 concentration

This method determines the target CO_2 concentration in an occupied classroom under stable conditions (steady-state). The classroom dimensions, the number of occupants, and the target air change rate must be known. The calculated steady-state concentration is compared with measurements taken continuously in the occupied classroom under steady-state conditions, i.e., the stabilised CO_2 concentration in an occupied classroom.

- Measure the classroom dimensions: width * length * height, and calculate the volume in cubic meters.

- Measure the concentration of CO_2 in outdoor air for at least five minutes before and after the experiment. Calculate the average for both measurements, which will be used as the average outdoor CO_2 concentration.

- Estimate the CO_2 generated as:

  CO_2 generation = number of people in the room * rate of CO_2 generation per person

- The rate of CO_2 generation per person depends on age, sex, weight, and metabolic activity. Consult Table 1 and Table 2 to determine the rate of CO_2 generation in each case in each case. Below are some typical values:

  - Seated students aged 6 - 11 years: 0.0031 litres per second = 0.186 litres per minute (lpm) per student

  - Adolescents: 0.0044 litres per second = 0.264 litres per minute (lpm) per adolescent

  - Adults (standing and speaking, average age between 30 to 40 years): 0.0061 litres per second = 0.366 litres per minute (lpm)

- Calculate the target outdoor airflow:

Target outdoor airflow = ACR(target) * Volume of the classroom

- Estimate the steady-state CO2 concentration ($C_{steady\text{-}state}$) using the following formula:

$$C_{steady-state} = \frac{CO_2\ generation + Target\ outdoor\ airflow * CO_2\ conc\ outdoor * 10^{-6}}{Target\ outdoor\ airflow * 10^{-6}}$$

where

$C_{steady\text{-}state}$ is in ppm

CO2 generation is in lpm

Target outdoor airflow is in lpm

CO2 concentration outdoors is in ppm

10^{-6} is a conversion factor for units

- Measure the CO2 to evaluate if the ventilation is adequate. If the steady-state CO2 concentration in the classroom is similar to the calculated $C_{steady\text{-}state}$, the target ventilation is established. If the measured CO2 concentration is above the $C_{steady\text{-}state}$, the target air change rate is not being met, and the ventilation configuration will have to be revised. Given that CO2 concentrations can vary during the day, allow a reasonable 20% deviation from the target value before taking any measures.

Note: these calculations can be made using the Excel spreadsheet provided in the annex of this guide.

Table 1: CO2 generation rates for ranges of ages and levels of physical activity, based on mean body mass in each age group. From Persily and de Jonge, 2017. Indoor Air, doi:10.1111/ina.12383.

			CO_2 generation rate (L/s)						
			Level of physical activity (met)						
Age (y)	Mean body mass (kg)	BMR (MJ/day)	1.0	1.2	1.4	1.6	2.0	3.0	4.0
Males									
<1	8.0	1.86	0.0009	0.0011	0.0013	0.0014	0.0018	0.0027	0.0036
1 to <3	12.8	3.05	0.0015	0.0018	0.0021	0.0024	0.0030	0.0044	0.0059
3 to <6	18.8	3.90	0.0019	0.0023	0.0026	0.0030	0.0038	0.0057	0.0075
6 to < 11	31.9	5.14	0.0025	0.0030	0.0035	0.0040	0.0050	0.0075	0.0100
11 to <16	57.6	7.02	0.0034	0.0041	0.0048	0.0054	0.0068	0.0102	0.0136
16 to <21	77.3	7.77	0.0037	0.0045	0.0053	0.0060	0.0075	0.0113	0.0150
21 to < 30	84.9	8.24	0.0039	0.0048	0.0056	0.0064	0.0080	0.0120	0.0160
30 to <40	87.0	7.83	0.0037	0.0046	0.0053	0.0061	0.0076	0.0114	0.0152
40 to <50	90.5	8.00	0.0038	0.0046	0.0054	0.0062	0.0077	0.0116	0.0155
50 to <60	89.5	7.95	0.0038	0.0046	0.0054	0.0062	0.0077	0.0116	0.0154
60 to <70	89.5	6.84	0.0033	0.0040	0.0046	0.0053	0.0066	0.0099	0.0133
70 to <80	83.9	6.57	0.0031	0.0038	0.0045	0.0051	0.0064	0.0095	0.0127
≥80	76.1	6.19	0.0030	0.0036	0.0042	0.0048	0.0060	0.0090	0.0120
Females									
<1	7.7	1.75	0.0008	0.0010	0.0012	0.0014	0.0017	0.0025	0.0034
1 to <3	12.3	2.88	0.0014	0.0017	0.0020	0.0022	0.0028	0.0042	0.0056
3 to <6	18.3	3.59	0.0017	0.0021	0.0024	0.0028	0.0035	0.0052	0.0070
6 to < 11	31.7	4.73	0.0023	0.0027	0.0032	0.0037	0.0046	0.0069	0.0092
11 to < 16	55.9	6.03	0.0029	0.0035	0.0041	0.0047	0.0058	0.0088	0.0117
16 to <21	65.9	6.12	0.0029	0.0036	0.0042	0.0047	0.0059	0.0089	0.0119
21 to < 30	71.9	6.49	0.0031	0.0038	0.0044	0.0050	0.0063	0.0094	0.0126
30 to < 40	74.8	6.08	0.0029	0.0035	0.0041	0.0047	0.0059	0.0088	0.0118
40 to <50	77.1	6.16	0.0029	0.0036	0.0042	0.0048	0.0060	0.0090	0.0119
50 to <60	77.5	6.17	0.0030	0.0036	0.0042	0.0048	0.0060	0.0090	0.0120
60 to <70	76.8	5.67	0.0027	0.0033	0.0038	0.0044	0.0055	0.0082	0.0110
70 to <80	70.8	5.45	0.0026	0.0032	0.0037	0.0042	0.0053	0.0079	0.0106
≥80	64.1	5.19	0.0025	0.0030	0.0035	0.0040	0.0050	0.0075	0.0101

Table 2: Values of physical activity levels (M). From Persily and de Jonge, 2017. Indoor Air, doi:10.1111/ina.12383.

Activity	*M* (met)	Range
Calisthenics—light effort	2.8	
Calisthenics—moderate effort	3.8	
Calisthenics—vigorous effort	8.0	
Child care		2.0 to 3.0
Cleaning, sweeping—moderate effort	3.8	
Custodial work—light	2.3	
Dancing—aerobic, general	7.3	
Dancing—general	7.8	
Health club exercise classes—general	5.0	
Kitchen activity—moderate effort	3.3	
Lying or sitting quietly		1.0 to 1.3
Sitting reading, writing, typing	1.3	
Sitting at sporting event as spectator	1.5	
Sitting tasks, light effort (e.g, office work)	1.5	
Sitting quietly in religious service	1.3	
Sleeping	0.95	
Standing quietly	1.3	
Standing tasks, light effort (e.g, store clerk, filing)	3.0	
Walking, less than 2 mph, level surface, very slow	2.0	
Walking, 2.8 mph to 3.2 mph, level surface, moderate pace	3.5	

Method 2 Example: Middle school classroom

Classroom of 65 m² with 16 adolescent students and one teacher.

- Classroom dimensions: width * length * height: 6.5 x 10 x 2.9 = 188.5 m^3
- Outdoor CO_2 exterior = 420 ppm
- CO_2 generation = (16 * 0.264 lpm) + (1 * 0.366 lpm) = 4.59 lpm (16 students and 1 teacher)
- Target air change rate, ACR = 5 h^{-1}
  (The target air change rate based on 14 litres per person per second (lps) ventilation:
  ACR = 14 liters per person per second * 17 persons * 3600 seconds/hour * 0.001 m^3/liter / 188.5 m^3 = 4.5 h^{-1})
- Required outdoor air flow: 5 * 188.5 = 942.5 m^3/hour = 15708 lpm

$$C_{steady-state} = \frac{4.59\ lpm + 15708\ lpm * 420 * 10^{-6}}{15708\ lpm * 10^{-6}} = 712\ ppm\ CO_2$$

- Measured steady-state values above 712 ppm CO_2 indicate an air change rate below the target, and thus additional measures will need to be implemented. Given that CO_2 concentrations can vary during the day, allow a reasonable 20% deviation from the target value before taking any measures.

Method 2 Example: Kinder garden classroom

Classroom of 50 m² with 12 children under 6 years and two caretakers.

- Classroom dimensions: width * length * height: 10 x 5 x 2.9 = 145 m³
- Outdoor CO_2 concentration = 420 ppm
- CO_2 generation = 12 * 0.186 lpm + 2 * 0.366 lpm = 2.964 lpm
- Target air change rate, ACR = 5 h^{-1}
  (The target air change rate based on 14 litres per person per second (lps) ventilation:
  ACR = 14 liters per person per second * 14 persons * 3600 seconds/hour * 0.001 m³/liter / 145 m³ = 4.9)
- Required outdoor air flow: 5 * 145 = 728 m³/hour = 12083 lpm

$$C_{steady-state} = \frac{2.964\ lpm + 12083\ lpm * 420 * 10^{-6}}{12083\ lpm * 10^{-6}} = 665\ ppm\ CO_2$$

- Measured steady-state values above 665 ppm CO_2 indicate an air change rate below the target, and thus additional measures will need to be implemented. Given that CO_2 concentrations can vary during the day, allow a reasonable 20% deviation from the target value before taking any measures.

Limitations of these methods

- The air in occupied spaces cannot always be considered well mixed. For instance, the air in a classrooms' central areas may be better mixed than the air in the corners or other peripheral areas. Tests should be carried out in different parts of the room to identify possible stagnant zones that may require extra ventilation.

- The calculations must be adjusted when filters or air cleaners are used to minimize exposure in combination with ventilation. The equivalent ACRs provided by ventilation and air cleaning are cumulative.

- CO_2 sensors should be calibrated before use.

- Unlike the virus, CO_2 does not degrade over time. Thus, the concentration of viable viruses in the air will decrease more rapidly than CO_2 concentrations. The difference will depend on various environmental factors such as UV radiation and temperature.

- The emissions of aerosols generated by people are not proportional to the emissions of CO_2. For instance, speaking loudly, shouting, or singing tends to emit many more particles and the increase with respect to breathing may be higher than the increase in CO_2 emission. Therefore, for identical CO_2 conditions, the risks of infection might be different.

- The measured values of ACR determined by Methods 1 and 2 on a given day will reflect the conditions of that day and can vary depending on the outdoor meteorological conditions.

- The accuracy of the results obtained by Method 1 may be affected by errors in identifying the start and end points in the CO_2 concentrations curve and by the response time of the CO_2 sensor.

- The amount of CO_2 generated by an individual varies depending on several factors, including age, sex, weight, and metabolic activity. The estimates used may affect the results obtained by Method 2.

Desirable characteristics of CO_2 sensors

- Provides data in a raw downloadable file such as .txt, .xls,.csv, or similar
- A time resolution of at least one data point per minute
- A screen that displays CO_2 levels in real-time
- Use of NDIR (non-dispersive infrared) technology
- Price range between 100 and 300 euros often provides the desired measurement quality

- Always follow the manufacturer's recommendations and calibration instructions.

- To test that the sensor is functioning correctly, measure the outdoor CO_2 concentration, which should be around 420-480 ppm. This value can be higher in dense urban areas during the day due to emissions from combustion sources. The accuracy of the instrument used should be taken into consideration.

PART II. INFECTION RISK ASSESSMENT

INFECTION RISK ASSESSMENT

The infectious risk can be assessed with a spreadsheet-tool, the Indoor Scenario Simulator, that calculates the number of viral particles in the air of a well-mixed room for which the room volume and the air change rate can be defined. It is available for download in many languages at *https://scoeh.ch/tools*. The scientific approach used in the tool is described in an article by Riediker and Monn (2020, Aerosol Air Qual. Res., doi:10.4209/aaqr.2020.08.0531). The tool uses mathematical modelling of the virus emission in the adult population for normal breathing, speaking softly and loudly at rest, and while being moderately or extremely physically active. It also allows simulation of the effect of wearing different types of masks. Thus, many different indoor scenarios can be simulated with a few mouse-clicks.

Virus emission and virus dose required for infection

How much virus does an average infected person emit?

How much a person emits depends on the viral load (viruses per milliliter of lung liquid) and how much aerosol volume that person emits. There is a very large range of viral emissions in the general population. The average person emits almost no virus. However, about ten percent of the infected population emits sufficient virus to pose a realistic risk, especially if they talk loudly and for prolonged periods in small, ill-ventilated rooms. Super-emitters (about 1 in 1000 infected people) can infect others even in very large halls. It is important to adapt the risk measures to these super-emitters.

How much virus is needed to get sick? What is the critical dose?

The dose necessary to infect humans is subject to ongoing research. For many viruses, a few hundred to a thousand plaque forming units (PFU) are sufficient to infect a human. PFUs are not identical to the number of viral copies determined by polymerase chain reaction (PCR) test, since several hundred "virus copies" can be present per PFU. When aiming to prevent infections, a "critical dose" that should not be exceeded can be defined as a few PFU, which corresponds to about 500 viral copies determined by PCR. For high-risk persons such as elderly, sick or immune-compromised patients, it seems advisable to define a lower critical dose of 100 or even 1 virus copy. Research on the minimal infective dose of SARS-CoV-2 is ongoing.

Simulations of school scenarios

We used the simulator to assess different scenarios in a classroom of 100 m² of 2.8 m height hosting 25 children and 1 teacher. We also look at the relevance of age and activity by assuming that either a teacher or a child 7 to 9 years old was the emitter. The scenarios described in Table 3 represent situations where either a child or a teacher becomes infected. The table shows calculations for a single class. That dose has to be multiplied by the number of classes per day to obtain the daily inhaled dose. Also, the scenarios assume there is perfect ventilation between classes and hence the virus concentration at the start of each class is zero. If this is not the case, the virus concentration throughout the class would be higher and so would be the risk. An (infected) teacher was assumed to talk loudly in front of the class for 30% of the class and then in a low voice to individual children for another 30%. In contrast, an often-talking (infected) child was assumed to talk for 10 % at low voice (discussions amongst children) and 5% loud voice (talking to entire class). Note that the risk of contracting the virus is elevated at daily doses above 500 virus-copies.

Table 3: Comparison of the inhaled viral dose received after 45 minutes for different classroom scenarios. This number has to be multiplied by the number of classes per day to obtain the daily inhaled dose from exposure at school

	Base scenario: inhaled dose after 45 minutes class	Teacher is infected "super-emitter"	Child is infected super-emitter = very high "adult" emitter
1)	Low ventilation (180 m³/h, here ACR=0.6 h^{-1}), nobody wears masks	3,177 virus copies	16 virus copies
2)	Low ventilation (180 m³/h, here ACR=0.6 h^{-1}), all wears medical masks	199 virus copies	5 virus copies
3)	Better ventilation (660 m³/h, here ACR=2.4 h^{-1}), all medical masks	143 virus copies	4 virus copies
4)	Better ventilation (1320 m³/h, here ACR=4.7 h^{-1}), all medical masks	100 virus copies	3 virus copies

It is important to note that the assumption of an infected child requires additional information from outside the simulator. A recent study suggests that children emit about half as many aerosols as adults when talking normally, though similar when talking loudly (*https://www.medrxiv.org/content/10.1101/2020.09.17.20196733v1.full.pdf*). Another study shows that the maximal viral load in children is about 100 times lower than adults, while the median is in a similar range to adults (*https://www.medrxiv.org/content/10.1101/2020.09.17.20196733v1.full.pdf*). We therefore assumed for these simulations that a "child super-emitter" emits as many viruses as a "high" to "very high" emitting adult (Table 4 shows the results for "very high"). The inhaled dose of children may be two- to three-fold over-estimated because the volume of air breathed per minute in the model corresponds to that of adults.

An important question is the activity of the teacher in the classroom before the start of the class. If this teacher is infected, the children will enter the classroom, in which there has already been some viral accumulation. Table 4 shows that a teacher working quietly with a mask leads only to a very small increase compared to the base scenario (199 inhaled virus copies by the children when they and the teacher enter at the same time, see Table 3). The increase of this value is relatively small even if the teacher wears no mask. However, the increase is substantial if the teacher sings/talks loud before the start of the class.

Table 4: Scenarios comparing the impact of different activities by an infected teacher during ten-minute preparation time in a poorly ventilated classroom. During the class, teachers were always assumed to talk loudly in front of the class for 30% of the time and then in a low voice to individual children for another 30% of time.

Advanced scenarios: Activities of teacher before start of the class		Teacher is infected "super-emitter" inhaled dose (children)
A)	Teacher wears a mask for 10 minutes before children enter room, teacher is quiet during this preparation time Low ventilation (180 m³/h, here ACR=0.6 h^{-1}), all wears medical masks during class	207 virus copies
A)	Teacher does not wear mask for 10 minutes before children enter room, teacher is quiet during this preparation time Low ventilation (180 m³/h, here ACR=0.6 h^{-1}), all wear medical masks during class	231 virus copies
B)	Teacher does not wear mask for 10 minutes before children enter room, teacher sings loudly during this preparation time Low ventilation (180 m³/h, here ACR=0.6 h^{-1}), all wear medical masks during class	3,281 virus copies

Simulations for other situations

We simulated a range of office situations, walk-in businesses such as small shops, boutiques, restaurants and discos; transportation when travelling by train, bus, car and air; documented super-spreading event (Please read the article "*https://aaqr.org/articles/aaqr-20-08-covid-0531*" for a full description of the findings).

Overall, these simulations document the positive effects of wearing masks and increasing ventilation. They also document the contribution of viral load, speaking and physical activity. The parameter driving the risk in most scenarios is the emission rate of the infected person; in most cases, the presence of a super-emitter (about one in 1,000 infected people) or very high emitter (1 in 100) was required to reach a critical number of inhaled virus copies. In very small rooms with poor ventilation (e.g. sitting in a car), a high emitter (1 in 10) was sufficient, especially if the emitter was singing or talking loudly. Wearing simple surgical/hygiene mask was very effective in almost all cases, assuming that the masks were a good fit and properly worn. However, masks are not always a good fit and properly worn in public spaces, which has to be considered in risk assessments.

The comparison to documented super-spreading events suggests that these infectious events could be explained by transmission via the airborne route (as opposed to contact transmission) and that an estimated dose of a few thousand virus copies may be sufficient to infect a large proportion of the exposed population.

DISCLAIMER

DISCLAIMER

- This document is provided for informational and educational purposes only. This document aims to provide guidance to optimise ventilation in school classrooms and reduce the risk of transmission of diseases, specifically the novel coronavirus SARS-CoV-2 and its associated disease COVID-19.

- The adherence to the information outlined in this document does not guarantee total prevention of disease transmission. Every situation and building is different, and users must accept that no scenario is entirely risk-free.

- This document should not be considered an exhaustive compilation of all available and suitable methods. Other reasonably designed methods will exist that can achieve similar results. This document is not intended to replace guidelines issued by governments or health authorities.

- The information contained in this document reflects the best available science at the time the document was compiled. The emergence of new information and scientific evidence may necessitate future revisions of this document.

- Every reasonable effort was made to ensure that the information in this document is correct and up to date. However, the information is provided without warranty of any kind. The authors disclaim any liability and in no event shall they be liable for any injury or damage to persons or property arising from the use or the inability to use the information contained in this report, including damages arising from inaccuracies, errors or omissions therein.

Guide for ventilation towards healthy classrooms

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