English version

INTERIM TECHNICAL NOTE

CO_2 monitoring for prevention and management in indoor environments in relation to the transmission of SARS-CoV-2 virus infection

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Interim technical note. CO_2 monitoring for prevention and management in indoor environments in relation to the transmission of SARS-CoV-2 virus infection. English version.
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To prevent the spread of the SARS-CoV-2 virus outbreak, it is critical to ensure indoor air quality to protect the health of citizens and workers. The report provides a set of recommendations for the use of indoor CO_2 measurements as a guide in relation to containing the risk of COVID-19 infection.

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Target of the document

The main recipients of this document are citizens, workers, employers, Protection and Prevention Services, managers and health authorities of the Prevention Departments of the National Health Service (NHS), each committed to their role, in the adoption and compliance with the COVID-19 action programs to respond to the needs of protection and prevention of the health of personnel and the community in the context of current knowledge.

CO_2 measurements must be interpreted as an indicator/guide, and depend on a number of factors such as: the number of people, the nature of the activities, the size of the rooms/spaces, the frequency and duration of opening doors, windows and balconies, the type of travel and the operating times of the mechanical ventilation system (Heating, Ventilation and Air Conditioning, HVAC), the positioning of instruments/automatic devices/sensors.

Introduction

To cope with the spread of the SARS-CoV-2 virus and its variants, in the many and different indoor environments, the Istituto Superiore di Sanità (ISS, the National Institute of Health in Italy) has provided a series of indications and recommendations: the goal is the optimization of outdoor air changes in a natural way or with mechanical systems and, more generally, ventilation. The recommended approach is not based on individual actions in their own right, but on a set of actions that must work simultaneously and in a complementary way to be effective in risk reduction (1-5) and that must be part of the organic risk prevention and mitigation strategy. Attention to indoor air quality has always been a real strength to promote and safeguard the health of citizens and at this time it is even more so, considering that, at present, most of the infections from SARS-CoV-2 and its variants occur in indoor environments and spaces.

Confirming the particular attention that must be paid to indoor environments, this report explores a series of technical aspects that constitute a general guide in the design and implementation of a correct strategy for monitoring carbon dioxide (CO_2) concentrations (expressed in parts per million-ppm volume/volume) through tools/automatic devices/fixed or portable sensors.

The main purpose of CO_2 measurements is to identify environments with poor air changes, to promote and implement daily operating methods of optimizing outdoor air changes in a natural way and with mechanical systems, to implement effective improvement and control programs in different aspects with a unified vision, before uncomfortable situations arise, poor productivity or health issues due to occupant exposure to various chemical, biological and physical agents – e.g. VOCs (Volatile Organic Compounds), Particulate Matter PM_{10}, $PM_{2.5}$, SVOC (*Semi Volatile Organic Compounds*), odours, bacteria, viruses, allergens, filamentous fungi (moulds) and moisture, etc.

At the operational level, it is important to take into account, as much as possible, a whole range of information to understand whether CO_2 measurements can be considered effective, to identify which actions need to be re-evaluated in the light of the results of measurements to improve outdoor air changes and ventilation, and if it is necessary to make changes to the measurement strategy (from the choice of environments/spaces, the type of device/sensor/technical characteristics, the positioning of the device/sensor, the fractional, continuous or one-off measurement modes). In particular, the measurements that are carried out depend in a complex way on a series of factors that as known have an influence on CO_2 concentrations in indoor environments: the number of people in normal conditions of occupation, the nature of the activities (physical effort), the characteristics and dimensions of indoor environments and spaces , the conditions of use, the frequency and duration of opening of doors, windows and balconies, the running and operating times of the ventilation system, the positioning of instruments/automatic devices/sensors.

Studies have shown that excessive crowding, ineffective ventilation, as well as long time spent in environments / spaces and failure to comply with prevention measures such as the use of the mask and distancing, can lead to an increase in CO_2 concentrations and increase the risk of infectious aerosols in indoor environments. In fact, it is increasingly recognized that in closed spaces, not suitably ventilated (<<< 3 L/s person) and overcrowded, at short/close distances or even at long range, a greater viral load is accumulated, if there are sources of emission carried by droplets and other aerosols released by the emitter (1-5). It follows that direct associations between high CO_2 concentrations and increased risks of COVID-19 transmission must be interpreted with extreme caution and require further in-depth work to avoid overestimations or underestimations (e.g., aerosol emissions are not proportional to CO_2 emissions; and with the same concentration of CO_2, the use of masks reduces the spread of aerosols). It is emphasized once again that the use of CO_2 measurements does not provide a direct measurement of air changes but these must be **interpreted as an indicator/guide that the air present in the environments/spaces is not**

replaced / changed with fresh air outside for too long or regularly or effectively and consequently the risk of infection could increase. In addition, the concentration of CO_2 is not related to the actual load of infection we do not know the rate of viral emission of people who have succeeded each other in the environment/space, both because the instruments / automatic devices/CO_2 sensors do not detect COVID-19. So, an environment/space with a certain number of people will have the same level of CO_2 concentration regardless of whether none of those present are infected, or whether one or more people are infected.

Continuous, periodic or regular (e.g., weekly) CO_2 measurements by the installation of automatic instruments/devices/sensors are technically simple compared to other substances emitted by occupants, but in order to better interpret and evaluate the reading of the data useful for the management of the environments / spaces, it is essential to develop an appropriate strategy for conducting measurements (in this regard, the choice of environments / spaces where to perform measurement activities must be carried out with particular attention to size, timing, frequencies, type of activity carried out, duration and level of employment: for example, a measurement taken during periods of low occupancy may provide CO_2 levels but be a misleading measure compared to risks at times of high crowding). This allows you to implement any specific corrective actions on the causes of risk avoiding or minimizing any problems. **The strategy must be drafted and modulated from time to time to respond to the specific purposes and purposes to be achieved, to adequately evaluate the results of the measurements, to adopt improvement actions and to identify early any incorrect behaviour in the management of window / balcony openings and anomalies in the functionality of mechanical ventilation systems (Heating, Ventilation and Air Conditioning, HVAC).** It is not necessary to permanently install automatic instruments/devices/CO_2 sensors in environments/spaces. In this path, it should be emphasized that CO_2 measurements are a monitoring activity to acquire a series of basic information, but alone they do not bring any improvement in indoor environments, if they are not part of the organic and integrated strategy of risk prevention and mitigation which solves the cause of high CO_2 concentrations; in practice it is useless to measure if they are not followed by the actions that lead to a real decrease in risk. In any case, the use of CO_2 measures does not mean that all other prevention actions/pillars can be replaced, reduced, reshaped or eliminated.

For the proper use of CO_2 measurements, another factor of extreme importance must also be considered in the organic prevention strategy, namely **the systematic carrying out of specific training, information, and awareness-raising activities on the advantages and limits that can be obtained with the measurement of CO_2 (it is not the measure of indoor air quality), on the daily actions to be implemented and on the behaviours to be adopted to be able to achieve the goal of a greater frequency in air changes and ventilation with external air.**

The methods of CO_2 detection in indoor environments can now be considered outlined and in current use. In this regard, the adoption of the UNI EN ISO 16000 part 26:2012 standard “Sampling strategy for carbon dioxide (CO_2)” and the indications on the operating methods present in the reports of the series *Rapporti ISTISAN* published by the GdS-ISS Indoor Pollution constitute a further step forward compared to what has been achieved so far in our country (*see* Appendix A1) and allow to operate correctly and uniformly.

The UNI EN ISO 16000 part 26:2012 standard contains clear indications on the principles of measurement, indicating that, although there are numerous methods of measuring CO_2, the instruments that work according to the principle of measurement of Non Dispersive Infrared (NDIR) (the most widespread) and Photoacoustic Spectroscopy (PAS) are those that allow to make continuous measurements in the range between 1 ppmv and 5000 ppmv (6).

With regard to the evaluation of the data collected, in the *Rapporto ISTISAN* 16/15 “Presence of CO_2 and H_2S in indoor environments: current knowledge and scientific literature on the subject”, there is an overview of the guide and reference values used in most countries at European and international level. The Report recommends using a maximum CO_2 concentration of 1000 ppmv; a value that is still considered valid in this pandemic period. In the UNI EN 16798-1:2019 standard there are references to indoor CO_2

concentrations above that of ambient-outdoor air to be achieved for good indoor air quality and the relative outdoor air flow rates (4 categories assuming a CO_2 emission of 20 L/h person, with indoor concentrations between 550 ppmv = 10 L/s person and 1350 ppmv = 4 L/s person).

The control by means of instruments/automatic devices/ CO_2 sensors and the time required to provide correct readings have been defined in the following documents:

- "Microclima, aerazione e illuminazione nei luoghi di lavoro. Requisiti standard. Indicazioni operative e progettuali. Linee guida" (7);
- UNI EN ISO 16000-26:2012 (6);
- UNI EN 16798-1:2019 (8);
- Reports of the series *Rapporti ISTISAN* of the GdS-ISS Indoor Pollution (Appendix A1).

Planning of CO_2 measurement activities in indoor environments

In this emergency context, awareness of the role played by indoor air quality and above all the impact that air changes and natural and mechanical ventilation have on the process of continuous improvement of the health of the population have strongly grown. It is evident the reversal of the trend compared to recent years on a series of aspects that have determined over time critical situations in indoor environments until now too often neglected (e.g., insulation, reduction of outdoor air changes, poor design of ventilation systems, inadequate performance of ventilation systems, little attention to the distribution of flows in all environments / spaces effectively and efficient, little attention to the choice of filters, operating times, poor maintenance of the systems and materials that pollute the air).

The control of outdoor air and ventilation changes generally expressed through the metrics of air changes per hours (h^{-1}), specific flow rates per person L/s or m^3/s*, represents an aspect of primary importance in the management of environments / spaces and in particular of indoor air quality it is relevant for health purposes in general and not only in relation to the pandemic, and therefore represents a higher quality indicator, well beyond COVID-19.

With regard to this last aspect, it is worth remembering the recommendations and indications to be adopted, in an organic way on a daily basis, during the period of stay in indoor environments, present in the reports of the series *Rapporti ISS COVID-19* n. 11/2021 (1-4), and those of the poster "Nuovo coronavirus. Consigli per gli ambienti chiusi" (i.e., New coronavirus. Tips for indoor environments) in March 2020 (5), which made use of the experience of the GdS-ISS Indoor Pollution.

CO_2 indoors is usually known as an indicator of emissions of bioefluents and odours coming mainly from the air exhaled by the occupants (it is the natural by-product of the metabolism of respiration that is warmer, with a high content of humidity and CO_2 present at about 4%v = 40,000 ppmv, whose levels correlate well with occupation and dissatisfaction provided that there are no other internal sources of CO_2 other than human presence) that are transported and dispersed in the environment/space by air movements (9-11). **It is known that it cannot be used as a "general indicator" of indoor air quality because it does not take into account other important sources of indoor pollutants such as materials, furnishings, curtains, paints, finishing treatments, glues, resins, silicones, cleaning products, combustions, etc., which emit VOCs, SVOCs, VVOC, particle material-PM_{10}, $PM_{2.5}$, CO and NO_2, in addition to the presence of filamentous fungi [moulds], allergens, bacteria and viruses just to name a few "classic" indoor pollutants.**

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* To switch from air changes per hours to m^3/h person, the following formula shall apply:

h^{-1} x ambient volume/area (m^3) = m^3/h divided by number of persons = m^3/h person.

To switch from m^3/h person to air changes per hours, should be applied instead this formula:

m^3/h person x number of people = m^3/h divided the ambient/area volume (m^3) = spare parts hour h^{-1}.

In **schools** values of:

- natural ventilation >0.5;
- mechanical ventilation between >2.5->5 (UNI 10339:1995 indicates external air flow rates between 4 and 7 L/s person).

In **inpatient rooms** values of:

- natural ventilation >0.5;
- mechanical ventilation > 2 (UNI 10339:1995 indicates external air flow rates of 11 L/s person).

The measurement of CO_2 is simple and is commonly used, but to do so you have to acquire different types of basic information on the environments / spaces, and consider the situations around the contour that can occur such as:

- dimensions, type of activity carried out, type and quality of ventilation, air filtration (e.g., filters classified according to UNI EN ISO 16890: 2017 as ISO ePM_{10}, ISO $ePM_{2.5}$ and ISO ePM_1 the ex F7-F9 of UNI EN 779), heating/cooling methods, combustion sources, construction and plant components, energy performance/redevelopment interventions, window change, etc.;
- activities and operating conditions of use (e.g., constant occupation from morning to evening with a substantial number of people varying over the course of the days or limited to short periods / one or more hours during the days, only in the morning, only in the afternoon or only in the evening with a substantial number of people that varies over the course of the days or limited to short periods / one or more hours), etc.

For a rational measurement strategy, the activities must be planned and carried out in the different environments / spaces for the following purposes:

- identify environments/spaces with poor air changes (do not indicate the flow of air) during the performance of activities with the presence of staff, users, patients, students, etc.;
- check if the rooms / spaces are equipped with regular air changes during the performance of activities with the presence of staff, users, patients, students, etc.;
- identify any improvement interventions aimed at the prevention or early detection of the possible risk (e.g., opening windows[**], balconies, checks on the operating conditions flow, flows, and on the operating times of the ventilation system, some of which are equipped with CO_2 measurement sensors), but also in the absence of activity when the environments/spaces are empty and it takes several hours before the CO_2 concentration returns to baseline levels;
- monitor CO_2 concentration levels in certain building environments/spaces during routine activities;
- verify the precise measurement of CO_2 levels, aimed at satisfying requests or solving problems brought to the attention of users;
- verify the effectiveness of the measures to optimize air and ventilation changes adopted in the different environments / spaces to also check their operating status over time.

As is known, in the UNI EN ISO 16000:26 standard "Sampling strategy for carbon dioxide (CO_2)" (6), two different principles for measuring CO_2 in the range between 1 ppm and 5000 ppm are indicated:

- the *Non Dispersive Infrared* (NDIR) (the most widespread);
- la *Photoacoustic Spectroscopy* (PAS).

Therefore, it is not recommended to use automatic instruments/ devices/sensors that do not comply with the UNI EN ISO 16000:26 standard, in order not to compromise the significance of the measurements or of the entire detection action by limiting and influencing the reading of the final result (different measurement principles may provide non-comparable results), such as:

[**] The opening surfaces must be evenly distributed on the external surfaces, avoiding the formation of pockets of air stagnation. The depth of the room relative to the aeration opening should not be more than 2 times the height of the room.
For health facilities, please note that door and window frames must have, in the upper part, devices to ensure natural ventilation of the halls, rooms and corridors. The windows best suited for inpatient rooms are those that open onto a solid wall not less than 1.20 m from the floor. Wards for contagious patients must comply with the ratio of windowed area greater than 1/5 of the floor of the room (7).

- electrochemical sensors (does not allow a selective measurement of CO_2; measurements are influenced by other substances);
- sensors that do not directly measure the concentration of CO_2 but return the data in CO_2 equivalents (eCO_2 or CO_2e).

In general, all instruments/automatic devices/sensors must allow to view, store and download the data of the measurements made to calculate parameters such as the averages of all the measurements made, therefore it is not recommended for routine monitoring activities those that visually provide only the instantaneous numerical value and that do not allow to store the measurements of the entire period. Such instruments/devices/sensors should also measure other parameters of interest to indoor quality such as temperature and relative humidity of the air at the same time. Another factor of extreme importance for the good final quality of the results is the calibration of the instruments/automatic devices/sensors.

Several countries have introduced in their legislation *ad hoc* rules relating to CO_2 concentrations in which precise indications are given on the concentration values and on the relative measurement times that have proved extremely useful in the management of environments/spaces. In this regard, in the *Rapporto ISTISAN* 16/15 "Presence of CO_2 and H_2S in indoor environments: current knowledge and scientific literature on the subject" (12), there is a rough examination of the main indications developed at European and international level (Table 1). The *Rapporto ISTISAN* recommends using in the evaluations a maximum CO_2 concentration of 1000 ppmv which represents a reference/guide for several EU and non-EU countries, a management "first approach" in the process of knowledge to indoor air quality not closely linked to health problems (health effects occur at significantly higher concentration levels); a value about 600 ppmv higher than the average value of CO_2 in ambient-outdoor air which is between 400 and 500 ppmv (with hourly and daily variations that are affected by the season and can be higher than 150 ppmv). In some cases, the nations have proposed values of 800-900 ppmv in order to limit the spread of viruses and often referring to the percentage of air already breathed by the occupants, when these values are exceeded, it is recommended to identify actions in terms of ventilation/air exchange and/or reduction of the number of people allowed in the environments / spaces that, in most environments. The value of 1000 ppmv is still considered adequate for the pandemic period; if this value is exceeded, actions must be identified in terms of ventilation / air exchange that in most environments corresponds to 10 L/s person: a value already recommended by the World Health Organization (WHO) (13) and contained in the standards UNI EN 16798-1:2019 (8) and ISO 17772-1:2017 (14); and/or the reduction of the number of people allowed in the rooms/spaces.

Specifically, CO_2 concentration values permanently exceeding 1000 ppmv during the occupation of the environments whose main physical characteristics and use are known indicate that outdoor air changes and ventilation are insufficient and need to be improved.

CO_2 concentrations generally increase over time in environments/spaces where users wear the surgical mask/FFP2 or where other additional measures are used such as air filtration with purifiers/purifiers (which do not provide outdoor air spare parts) equipped for example with *High Efficiency Particulate Air filter-HEPA* or *Ultra Low Penetration Air* filters -ULPA, whose performance has been verified according to the UNI EN 1822: 2019 standard or filters with minimum removal efficiency ISO $ePM_1 > 70\%$ ISO $ePM_{2.5} > 80\%$, ISO $ePM_{10} > 90\%$ verified according to UNI EN ISO 16890:2017 (Appendix A2).

*** percentage of air already breathed by occupants=ratio of CO concentration$_2$ in the indoor air (C_{ia}) minus co concentration$_2$ in the outdoor air (C_{oa}) divided by the concentration of CO_2 in the exhaled air (C_{ea}) multiplied by 100: Fr= C_{ia}-C_{oa}/C_{ea} x 100. This percentage shall be considered valid if less thanlthe 1%.

Table 1. Guide values of indoor CO_2 in *ad hoc* documents and in the legislation of the different countries*. Update of the Table 1 of the *Rapporto ISTISAN* 16/15 (12)

Nation	Guide value
European Union	
Belgium	**1.620 mg/m³** (900 ppmv) per 8 hours (15) **2160 mg/m³** (1200 ppmv) per 8 hours (15)
Finland	S1 **1.350 mg/m³** (750 ppmv) (16)S2 **1.710 mg/m³** (950 ppmv) (16)
French	**1.440 mg/m³** (800 ppmv) (17, 18) **1.800 mg/m³** (1.000 ppmv) (19, 20)
Germany	**1.800 mg/m³** (1.000 ppmv)
	<**1,800 mg/m³** (1,000 ppmv) harmless concentration; between **1800 mg/m³** (1000 ppmv) and **3600 mg/m³** (2000 ppmv) high concentration; > **3600 mg/m³** (2000 ppmv) unacceptable concentration
Norway	**1.800 mg/m³** (1.000 ppmv)
Netherlands	schools: **1,710 mg/m³** (950 ppmv) new construction (21) **2160 mg/m³** (1200 ppmv) (21)
Portugal	**1.800 mg/m³** (1.000 ppmv) (22) **2.250 mg/m³** (1.250 ppmv) (22)
Spain	**1.440 mg/m³** (800 ppmv) (23) **1.800 mg/m³** (1.000 ppmv) (23)
Extra-European Union	
Brazil	**1.800 mg/m³** (1.000 ppmv)
Canada	**1.800 mg/m³** (1.000 ppmv)
Japan	**1.800 mg/m³** (1.000 ppmv)
	Schools: **2,700 mg/m³** (1,500 ppmv) average concentration on the school day
Hong Kong	**1.440-1.800 mg/m³** (800-1.000 ppmv) per 8 hours
United Kingdom	**1,800 mg/m³** (1,000 ppmv), level used if the goal is energy saving; **972 mg/m3** (1750 ppmv) renovated building
	schools: (24) **1,800 mg/m³** (1,000 ppmv) during the period of occupation (classrooms equipped with HVAC and HVAC + natural ventilation) **2,700 mg/m³** (1,500 ppmv) for mhours than 20 consecutive minutes each day (classrooms with natural ventilation) **3,600 mg/m³** (2,000 ppmv) maximum concentration that should not be exceeded for mhours than 20 consecutive minutes each day (classrooms with natural ventilation)
Republic of Korea	**1.800 mg/m³** (1.000 ppmv)
Singapore	**1.800 mg/m³** (1.000 ppmv) per 8 hours
United States	CDC (25) **1440 mg/m³** (800 ppmv)
	ASHRAE **1.800 mg/m³** (1.000 ppmv) According to the ASHRAE 62.1:2016 standard, the limit value for the acceptability of indoor air quality is established as equal to a difference between indoor and outdoor CO_2 concentration of **1260 mg/m³** (700 ppmv) and corresponds to ventilation conditions considered uncomfortable (body odor) by about 20% of the people present.
	Illinois **1.800 mg/m³** (1.000 ppmv)
Taiwan	**1.800 mg/m³** (1.000 ppmv)

* Where the reference document does not report the conversion factor mg/m³ to ppmv for CO_2, the WHO conversion factors reported in the Indoor Air Quality Guidelines (WHO, 2010) were used, referring to the temperature of and pressure of 760 mmHg: 1 mg/m³ 25°C= 0.556 ppmv; 1 ppmv = 1.8 mg/m³.

In parallel with the planning of CO_2 measurements, it is necessary to carry out specific, effective and regular training, information and awareness activities on the advantages and limitations of these measurements (e.g., to allow the duration and frequency of air changes to be adapted to the characteristics of the environments/spaces, to climatic conditions and their use, to overcome indications of danger or false reassurances) and on good habits that must be adopted by all parties involved with different capacities of action and responsibilities such as:

- employees (teachers, students, patients, workers);
- users (customers of restaurants, bars, shopping centres, gyms, means of transport);
- responsible and managers of the optimization of outdoor air and ventilation spare parts.

Basic information required for CO_2 measurement

In the preparation phase of the plan for measuring the levels of CO_2 concentrations, it is important to collect a series of data characteristic of the environments/spaces alongside the basic information that describes in detail the most significant aspects of the multiplicity of activities that take place there, and that play an essential role in the representativeness of CO_2 measurements.

It is necessary to consider:

- physical characteristics of the rooms/spaces (e.g., dimensions and volumes of the rooms, layout, presence and size/area of doors, windows, types of fixtures, furniture, curtains, position of radiators/radiant elements for heating, energy performance certification, etc.);
- plant characteristics and the methods with which the air exchange is carried out (e.g., natural ventilation or HVAC), the frequency of air changes, the type of operation/activation, the distribution and positioning of the supply and extraction intakes in the different environments in order to obtain a good uniform distribution-ventilation in every part of the environment/space the positioning and type of any air filters (UNI EN ISO 16890:2017), the frequency of replacement of filters, etc.*;*
- any modification of the environment/spaces (e.g., extraordinary openings of the windows, increase in HVAC capacities will change the conditions of balance and consequently the representativeness);
- conditions of use that can be had during the performance of daily activities (well-defined presence of people in constant, occasional or temporary time);
- activities carried out indoors (e.g., office, lesson, study, sports, commercial, etc.), the conditions of use of the areas and premises (e.g., continuous, daytime, afternoon, opening hours to the public, etc.);
- age, gender and type of activity carried out (light, medium, heavy: the volumes of CO_2 produced are closely linked to the metabolic activities that push up the emission and can make a lot of difference, the same applies to viral loads) of the occupants of the environments;
- presence of combustion sources;
- presence of pets;
- organizational measures taken;
- optimization of the opening times of the windows and balconies according to the number of people, the activities carried out in the environment/area and the volume of the space to avoid uncomfortable/discomfort conditions (hot or cold air currents directly on people) and the correct functioning of the ventilation system and the verification of compliance with reference values and prescriptions.
- activities and programs of training and updating mandatory for staff, those of awareness, any recommendations produced, information programs for students on the issues of indoor air quality.

In cases where it is necessary to find further information, it may be useful to fill in survey questionnaires similar to those proposed in the volumes of the series *Rapporti ISTISAN* no. 19/17 and no. 20/3 (26, 27).

Measuring points for indoor environments

In all indoor environments the choice of the position where to place the instruments/automatic devices/sensors is of great importance, in order to obtain representative and useful results to formulate recommendations for the correct prevention actions to be adopted (since environments/spaces little frequented and of large volume are difficult to evaluate).

The UNI EN ISO 16000:26 provides for environments / spaces with an area of up to 50 m^2 (135-150 m^3) a single measuring point preferably located in the centre of the environment. In larger environments/spaces it is necessary to place more than one measuring point to ensure the measurement of any possible inhomogeneities/gradients that affect the CO_2 concentration.

The choice of the measuring point in environment/spaces and the characteristics of the instruments/automatic devices/sensors can result in differences in the measured CO_2 concentration values of up to 250 ppm.

In making the choice of the measurement point in an environment/space (office, classroom, hospital, gym, banks, post office, cinema, shopping centres, means of transport) it is necessary to position the detection equipment according to the following criteria specified in the UNI EN ISO 16000 part 1 and 26 and in the volumes of the series *Rapporti ISTISAN* of the GdS Indoor Pollution (Appendix A1):

- at a height of about 1.5 m from the floor (in the case of classrooms where students are sitting at the desk, a height of between 1 and 1.5 m from the floor);
- at a distance of about 1.5-2 m from people;
- at a distance of not less than 1,0 m from bookcases, cabinets or other obstacles;
- away from leakage of natural air currents (e.g., near the windows, entrance doors) or forced by walls or ceilings that can channel the air in obligatory directions;
- away from sources or heat sources (e.g., close to the radiators of fixed or portable radiators, fan coils, spotlights, etc.).

Timing and frequency of CO_2 measurements

In the various studies carried out and in the data reported in the literature, it is noted that CO_2 concentrations vary throughout the day and the cause of this significant variability is associated with the number of occupants, the type of activity carried out, the methods of opening/closing windows and balconies and running the ventilation system. Therefore, the choice of times and frequencies of the measurements must be carefully planned, otherwise misleading and non-representative measurements of the use of the environments/spaces throughout the day will be obtained. This is because instantaneous/rapid/spot measurements of very limited duration up to 1 hour do not help to respond to any of the objectives (e.g., possible transient events that can cause a momentary accumulation of CO_2; the failure to reach the state of "equilibrium" or "steady state"), taking into account that "stabilization/acclimatization" of the instrument takes at least 30 minutes. It is necessary to plan in an appropriate way both the times and the frequency with which to carry out the measurements, remembering that **the strategy for measuring CO_2 concentrations is drawn up and modulated from time to time to respond to the objectives, specific purposes and purposes that are to be achieved with the measurement activities**. The duration of fractional or continuous measurement depends on the specific purpose of the measurement activity and must take into account the different factors already mentioned that may influence the representativeness of the entire strategy. **In general, the data that interests you is the one that describes the whole day with the presence of people as an average of all the measures in the period of activity/occupation and the duration of the measurements must be equal to the time that is associated with the reference / guide value that you want to use in the comparison.** To give an example in the case of offices, schools, health facilities, banks, post offices, commercial activities, just to name a few where every day of the week and at set times most of the activities are carried out, there is a need to make continuous measurements that cover the entire schedule with the presence of people (schools h 8-14, offices h 8-17, post office h 8-19, gyms h 7-22) and surveys that cover the intervals of non-activity, in the absence of workers, students, patients, users, complementary to 24 hours (h 14-8, h17-8, h 19-8, h 22-7). In some cases, extremely variable situations can occur due to different factors and therefore it is necessary to program the measurements appropriately, with a careful analysis of the use scenarios. **The duration of the measurement campaign must be at least weekly to be repeated several times during the different seasons** because the CO_2 levels vary throughout the year, depending on the temperature of the outside air, which influences the behaviour of users regarding the opening of windows, balconies and doors. This allows to obtain a precise knowledge of the situation, to identify critical points and moments (e.g., hours, occupation) and adopt management methods that improve the quality of the environments/spaces. **This period is generally the one necessary to typify an average CO_2 trend over time and to describe, in the most representative way possible, the environments/spaces.**

The measurements thus obtained allow to understand, in the absence of activity, the ability of the environment to return to its basic levels of CO_2 (it is another element of evaluation to identify bad air/ventilation changes and to intervene) and if the instrument/device/sensor works (CO_2 close to 400-500 ppmv).

Given the wide variety of characteristics of the environments/areas and the period and levels of employment, Table 2 contains some useful indications for the development of the monitoring strategy and the use of CO_2 measures.

Table 2. CO_2 measurements, characteristics of environments/spaces and duration of monitoring activities

Characteristics	Area and volumetries	Duration and frequency of employment	Suitability of CO_2 measurement	Duration of the CO_2 measurement period
Domestic environments, Classrooms for teaching and training, Specialized laboratories (musical, linguistic, computer, etc.), Office rooms, Inpatient rooms, Study rooms, Meeting rooms, Waiting areas	Small environments 50 m^2 with volumes up to 150 m^3	Permanent and continuous throughout the days	YES	It must cover the whole day Evaluation of activity intervals and non-activity. Even 1 point can be enough
Changing rooms, common spaces (e.g., corridors)	Small environments 50 m^2 with volumes up to 150 m^3	Short, transient and variable over the course of the days or limited to short periods	YES, but great care should be taken especially if the CO_2 concentrations measured are very low (< 400 ppmv) or very high (>1500 ppmv); it may be necessary to move the device/sensor to another position within the environment/space, or remodulate the measurement times to obtain more representative measurements. Possibility of pockets in which the air stagnates. CO_2 changes rapidly as people move.	It must cover the whole day. Evaluation of activity intervals. The data collected and stored must be treated with great caution. Despite the uncertainties, it is still important to acquire them and take them into account. Even 1 point can be enough
Classrooms for teaching and training, University classrooms Specialized laboratories (musical, linguistic, computer, etc.), Libraries, Office rooms, Inpatient rooms, Clinics, Waiting areas, Meeting rooms, Gym rooms, Commercial spaces, Bars, Restaurants, Means of transport	Medium rooms 60-350 m^2 with volumes up to 950 m^3	Permanent and continues	YES, great attention should be paid to the possibility of pockets in which the air stagnates.	It must cover the whole day Evaluation of activity intervals and non-activity. At least 2 points are needed in the most occupied areas to provide representative information on CO_2 concentration levels.

Characteristics	Area and volumetries	Duration and frequency of employment	Suitability of CO_2 measurement	Duration of the CO_2 measurement period
Booking offices, Commercial spaces, Bars, Canteen, Restaurants, Means of transport	Medium rooms 60-350 m^2 with volumes up to 950 m^3	Short, transient and variable over the course of the days or limited to short periods	YES, but great care should be taken especially if the measured concentrations are very low (< 400 ppmv) or very high (> 1500 ppmv); it may be necessary to move the device/sensor to another position within the environment/space, or remodulate the measurement times to obtain more representative measurements. The greater the volume of space, the longer it takes to achieve concentration stabilization.	It must cover the whole day Evaluation of activity intervals and non-activity. The data collected and stored must be treated with great caution. Despite the uncertainties, it is still important to acquire them and take them into account. You need at least 2 points
Aula Magna, Auditorium, Theatres, Shopping Malls, Airports, Railway Stations, Sports Halls	Large rooms over 350 m^2 with volumes over 1000 m^3	Limited to short periods	YES, great care must be paid. The greater the volume of space, the longer it takes to achieve concentration stabilization. The measurement may be affected by the tank effect of the environment/space.	It must cover the whole day Evaluation of activity intervals and non-activity. Unreliable measurements are obtained and the data collected and stored must be treated with extreme care. Despite the uncertainties, it is still important to acquire them and take them into account. More measuring points are needed in the busiest areas.

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Appendix A

A1. Documents of the GdS-ISS on Indoor Pollution

The references of the documents that the GdS-ISS on Indoor Pollution has published are reported, in order to implement harmonized actions at national level to reduce and mitigate exposure to *indoor* pollution and health effects, to improve the control of risks in indoor workplaces, to raise awareness of behaviour and make the population aware of one of the issues of great relevance and priorities for our country. All the reports listed below are in Italian, with an abstract in English and are available at https://www.iss.it/rapporti-istisan:

- *Rapporti ISTISAN 20/3*
  Indoor air quality in schools: strategies for monitoring chemical and biological pollutants

- *Rapporti ISTISAN 19/17*
  Indoor air quality in schools: strategies for monitoring chemical and biological pollutants

- *Brochure*
  "Booklet on indoor air quality "The air in our home": 2017

- *Rapporti ISTISAN 16/15*
  Presence of CO_2 and H_2S in indoor environments: current knowledge and scientific field literature

- *Rapporti ISTISAN 15/25*
  Microclimate parameters and indoor air pollution

- *Rapporti ISTISAN 15/5*
  Monitoring strategies to assess the concentration of airborne asbestos and man-made vitreous fibres in the indoor environment

- *Rapporti ISTISAN 15/4*
  Workshop. Indoor air quality: current national and European situation. The expertise of the National Working Group on indoor air. Istituto Superiore di Sanità. Rome, May 28, 2014. Proceedings

- *Rapporti ISTISAN 13/39*
  Workshop. Issues related to indoor air pollution: current situation in Italy. Istituto Superiore di Sanità. Rome, June 25, 2012. Proceedings

- *Rapporti ISTISAN 13/37*
  Monitoring strategies of biological air pollution in indoor environment

- *Rapporti ISTISAN 13/4*
  Monitoring strategies for Volatile Organic Compounds (VOCs) in indoor environments.

A2. Are mobile air purifiers really a solution?

As already reported in the *Rapporto ISS COVID-19* n. 11/2021 on interim indications for the prevention and management of indoor environments in relation to the transmission of SARS-CoV-2 virus infection (4), in the case in which it is not possible to improve in any way the external air changes with the opening of the windows/balconies and ventilation and we want to equip the environments/spaces with purification systems/devices, the choice must be made with the utmost attention by evaluating case by case and *first of all* if the solution is seen in the short term, or if it is likely to be long-term (more than one year), or if it is at the service of environments/spaces dedicated to temporary isolation.

A variety of air purifiers (also known as air purifiers) are available on the market that are mobile/fixed on the wall or installed inside ventilation systems. The different air cleaners/purifiers use different technologies and mechanisms of action depending on the nature of the chemical and biological pollutants on which they generally act. Some air purifiers/purifiers have monitoring and control functions (e.g., cleaning status or filter replacement) and the possibility of programming their operation.

Some air cleaners/purifiers use more than one purification technology to achieve their removal/inactivation goals; they can be classified into four categories depending on the technology and the principle of operation, based on:

- mechanical filtration, which capture and remove the particle-PM material such as those equipped with very high efficiency filters *High Efficiency Particulate Air filter-HEPA*, *Ultra Low Penetration* Air-ULPA, tested according to the UNI EN 1822: 2019 standard;
- generation and emission/addition of reactive components ions, ozone, electrofilters (tested according to the UNI 11254: 2007 standard), which eliminate or transform unwanted pollutants (e.g., remove particular matter-PM, react with pollutants, inactivate microorganisms) such as ionizers, ozone generators, plasma, PCO photocatalytic oxidation. They can release/generate primary and secondary pollutants, e.g., ozone or persistent and dangerous purification by-products such as hydroxyl radicals, oxygen reactive species, UFPs, etc. Some devices use adsorbent filters to retain some of the generated by-products;
- use of UV-C/UVGI that inactivate bacteria and virus contaminants. They can also use very high HEPA efficiency filters;
- simultaneous use of multiple phases/technologies such as filtration + adsorption (for example: HEPA filters + activated carbon filters or UV-C + HEPA filters; UVC + electrostatic filters + adsorbent filters in activated carbon or other adsorbent substances) to simultaneously remove particulate matter-PM, volatile organic compounds-VOCs and other gaseous substances. The order in which the technological phases follow one another is very important to determine their effectiveness; for example, activated carbon filters placed upstream of HEPA filters or upstream of a technology that can produce unwanted by-products will be less effective. Compared to the control of particle-PM material, the control of pollutants in the gas phase is much more complex. Adsorbent filters (e.g., activated carbon) have been shown to be effective for the many pollutants in the VOC family, and during their use do not produce potentially harmful chemical by-products. Adsorbent filters have a finite adsorption capacity, and therefore, they must be replaced regularly to avoid becoming themselves a source of the pollutants it has adsorbed during operation.

Therefore, it is necessary to acquire all the information on the technology of air cleaners/purifiers, such as:

- type of technology used by the air cleaners/purifiers;
- type of air filters used by the air cleaners/purifiers (the minimum efficiency must have been tested according to UNI EN ISO standards; it is the most useful parameter to understand the efficiency of filter removal. In general, the higher the filter classification, the higher the removal efficiency of a filter e.g. HEPA H14, ULPA U17, ISO ePM1 > 70% ISO $ePM_{2.5}$ > 80%, ISO ePM10 > 90% or higher combinations or classifications);
- power of the air cleaners/purifiers - air flow = the amount of "clean" air needed, must be adequately sized according to the volume/square footage of the environment and air changes/ventilation. Today the *Clean Air*

*Delivery Rate-CADR** expressed in m³/h is used a lot, which represents the rate of filtered air emitted by the air cleaners/purifiers which represents one of the useful parameters to understand the effectiveness;

- presence of devices for measuring pollutants in the air that allow to modify the flow rate;
- *layout* of the environment;
- type of activity carried out;
- number of people;
- time and mode of operation, for example, must be switched on every morning at the beginning of the activities and must be turned off at the end of the day. The operating time has a great influence on the performance and on the ability to reduce pollutant concentrations;
- correct positioning in the environment with respect to windows, balconies, doors and workstations (e.g., direction of the generated air flows);
- possible direct release or formation of chemical by-products secondary to purification that may be persistent and dangerous (ROS oxygen reactive species, ozone, hydroxyl radicals, precursors, ultrafine particles-UFP, nanoparticles, other unknown by-products);
- data and performance certifications available on specific tests carried out in similar real environments that demonstrate proven efficacy and safety in the conditions of use both against the SARS-CoV-2 virus and its variants, and on chemical emissions. Test data and reports often make it difficult to interpret performance by not reporting adequate information on the test conditions, the tests carried out and the test methods used. Certifications and test reports shall provide results on emissions of primary or secondary products (the formation of by-products) that may form during operation. This is an aspect that is still not being adequately addressed and that deserves great attention.

The reports shall contain the volume of the test chamber or environment tested, the air exchange rates and whether these were constant, the concentrations used, the occupancy pattern, and possible variations in parameters between the white and test conditions.

The results obtained in a test laboratory do not necessarily mean that the purifier/ purifier will be as effective in the real environment (environmental conditions may be different, which vary significantly from space to space, given the presence of different types of materials/furnishings, different surfaces with different types of finish, etc., combined with the variability of pollutants already present e.g. VOCs and associated secondary chemical reactions that they can be an important indoor source of particle material, UFP and nanoparticles).

In the COVID-19 context it is absolutely necessary to know the impacts in the use of air purification/purification devices to ensure that their use does not lead to the replacement of a biological risk with a chemical risk (the addition of reactive agents can initiate unwanted chemical reactions with the formation for example of formaldehyde, UFP, nanoparticles, etc.).

There should be no confusion between efficiency and effectiveness. A purifier/purifier can have a high efficiency obtained and certified in the test laboratory, usually expressed as a percentage of reduction %, or in percentage of % reduction of the pathogen in minutes/hour (or removal of logs compared to time), but can have a very low effectiveness if the air flow is too low compared to the volume of the environment/space, or if the operation is intermittent or if the filters are clogged or too loaded. Efficiency is a simple parameter for purifiers/purifiers that use filtration, while it is less useful for those that generate and emit/add components or for those that use multiple phases/technologies simultaneously. Therefore, it is necessary to request and acquire all this data and not be limited to the generic declarations of performance present in the commercial materials or in the test reports provided;

- Performance and efficiency of technologies over time (aging) as they affect the performance or formation of primary and secondary pollutants/by-products;

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* CADR=A measure of air cleaner performance, defined as the amount of contaminant-free air delivered by the device, expressed in m³/h.

- Noise of the air cleaners/purifier that can affect the timing and frequency of use/shutdown for possible annoyances by users. The noise level/class expressed in dB(A) to be considered is that during operation at maximum air flow. Settings with lower air flow can produce less noise, but the purifier/purifier will also be less effective at removing pollutants. Noise-related operating hours reduces potential effectiveness. The noise levels/class must be present in the documentation, the definition of silent is not enough;
- Operating and maintenance costs. Costs are important because “air cleaning” must be a continuous process and purifiers/purifiers require continuous and regular cleaning and maintenance, such as filter replacement, UV-C lamps, etc. to remain effective.

The air cleaners/purifiers do not dilute and do not remove all pollutants as it happens when the exchange of outdoor air is carried out (e.g., see the concentration of CO_2 and the RU%). It should be noted that the recirculating air supplied by the purifiers / purifiers does not in any way replace the air changes with “fresh outside air” (often considered in terms of equivalent air changes), and therefore the windows and balconies must not remain closed for the entire duration of use but must still be opened.

Therefore, the use of air cleaners/purifiers cannot replace outdoor air changes/ventilation, the use of a mask, physical distancing and other barrier measures.

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