Reducing infection risk and optimization of airing concepts for indoor air quality by accurate aerosol and CO_2 measurement

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ABSTRACT

Since the outbreak of the SARS-CoV-2 pandemic and the findings about the virus transmission route through aerosols, indoor air quality is a major topic when it comes to efforts to contain the spread of SARS-CoV-2 in the population.

Most calculations of infection risk, however, still rely on CO_2 as a proxy for exhaled aerosols. This assumption is no longer valid when air filtration devices are used, arising the need to include actual measured aerosol concentration into the calculation of indoor infection risk. To close this gab, a version of Wells-Riley equation, extended to include the effect of air filtration into determination of reproductive number, is introduced and applied to measurement data from indoor air quality during school lessons. The results show, that taking only CO_2 into account will overestimate the real infection risk from aerosols by 20% in the cases without air filtration and by 60% in the cases with air filtration.

Furthermore, measurement results varied strongly between different classrooms. This indicates that general airing recommendation, as applied during these tests, are not enough to assure a healthy environment and more individual measurements are necessary.

INTRODUCTION

One of the main modes of transmission of SARS-CoV-2 is transmission through direct contact or droplets (> 5-10 µm) that an infected person will expel when coughing, sneezing, or talking (WHO (2020)). This mode of transmission is very well known from other common diseases, such as influenza, and therefore the preoccupations to take, such as keeping distance or covering the mouth while coughing, are quite clear and also supported from the vastly majority of the people.

However, the airborne transmission route, another main route of transmission for SARS-CoV-2 (Morawska and Milton (2020), Li et. al. (2020), WHO (2020), CDC (2020)), in not so easy to prevent as it involves the transmission over very small (< 1 µm) exhaled aerosols that can stay in the air for a very long time and thus accumulate in closed spaces and travel longer distances than the bigger droplets responsible for direct infection. So, one does not only face infection risk from close contact to an infectious person but also from sharing a room with one. This brings the focus to indoor air quality, and especially aerosols, when we aim to reduce the infection risk in closed spaces. And not only SARS-CoV-2 spreads through aerosols. Also, other well-researched diseases such as influenza use this transmission route (Moser et. al. (1979)). Consequently, need and demand for devices that can measure aerosol influence on indoor air quality has increased significantly.

Up to now, indoor air quality (IAQ) was primarily associated with maintaining a pleasant environment. Monitoring IAQ focuses mainly on parameters such as TVOC, CO_2, temperature as well as relative humidity, and sometimes also particulate matter (PM2.5 and PM10). All these parameters can be measured quite easily with rather simple equipment resulting in a variety of low-cost devices to monitor indoor air quality. However, measurements from low-cost devices needs to be treated with caution as quality issues regarding long term stability and comparability are not uncommon.

Since the findings of airborne transmission of SARS-CoV-2, aerosols have gained more and more attention in the discussion about IAQ and indoor infection risk. Unlike gases such as TVOC and CO_2, accurate measurement of aerosol concentration, especially in the size range of exhaled aerosols, is not easy to achieve and involves complex measurement technique. Many studies about infection risk in closed spaces therefore focus on measuring CO_2 as a proxy for exhaled aerosol laden air neglecting differences in gas and aerosol dynamics. This approach might lead to acceptable results for cases where the only method applied to enhance indoor air quality is introducing fresh air. However, there are several cases where lowering infection risk by introducing fresh air either is not feasible (e.g. when outside temperature is very low) or simply not possible (e.g. in a room with very few or small windows). In these cases, air purifiers can be the method of choice reducing indoor infection risk by a factor of 6 as shown by Curtius et. al. (2020).

With filtering devices in operation, aerosol concentration needs to be considered when determining the infection risk. This can be done by using an optical aerosol spectrometer to accurately measure aerosol concentrations. In the present study,

a device combining aerosol spectrometer and CO_2 sensor was used to measure infection risk in classrooms during classes in a public school in Germany. Purpose of the project was to validate official airing guidelines and give suggestions to improve indoor air quality.

METHODS

One very common approach to address the risk of indoor airborne infection transmission is to calculate the basic reproductive number for a given situation. The reproductive number represents the number of people that will be statistically infected by one infectious person in the room. Rudnick and Milton (2003) derived a formular to calculate the basic reproductive number from Wels-Riley-Equation using CO_2 as a proxy for exhaled aerosol concentration; where n is the number of people in the room, $\bar{f}$ is the mean rebreathed fraction of air over the residence time t of the people in the room and q is the generation rate of infectious quanta by the infected person in the room.

$$R_{A0} = (n-1)\left[1 - \exp\left(-\frac{\bar{f}qt}{n}\right)\right] \quad (1)$$

The rebreathed fraction of air is estimated from the increase in CO_2 concentration by expelled air according to Equation (2), Where $C(t_i)$ is the CO_2 concentration in the room at time t_i, C_0 is the CO_2 concentration in the unoccupied or properly aired room and C_a is the CO_2 concentration in exhaled air.

$$f(t_i) = \frac{C(t_i) - C_0}{C_a} \quad (2)$$

Critical for the calculation of reproductive number is the estimate of the quantum generation rate q that defines how infectious one person is assumed to be. It can be derived from modeling real outbreaks that occurred under known circumstances (for example outdoor air exchange rate). Very infectious diseases such as measles ($q = 570\ /h$) have a high quantum generation rate and less infectious diseases such as for example rinovirus 16 ($q = 1 - 10\ /h$) equal to a low quantum generation rate (Rudnick and Milton (2003)). In the present study we assumed a quantum generation rate of $100/h$ was assumed, which coincides with the findings of Kriegel et. al. (2020) who reported quantum generation rates of $116/h$ for school lessons.

Another important factor is the half-life of the airborne virus. SARS-CoV-2 is expected to remain viable for 1.1 to 3 hours (Curtius et. al. (2020)). For the evaluation of the infection risk measurements, half-life of virus is not considered as duration of school lessons with 45 min is below half-life given in literature.

Including aerosol concentration into infection risk calculation

Equation (1) allows to calculate the reproductive number at any time for a specific scenario based on measurement of actual CO_2 increase in the room. However, especially when air filtration devices are used CO_2 is not a good proxy for exhaled aerosol concentration in the room anymore. Given the technical principle aerosols are constantly filtered from the air whereas CO_2 concentration is not affected by the air filtering device. In this case, reproductive number calculated based on CO_2 will overestimate the real reproductive number. To avoid this and to increase explanatory power, aerosol concertation needs to be included into the calculation. This can be done by multiplying the rebreathed fraction f according to Equation (2) with the current decrease in aerosol concentration a (Equation (3)). The latter can be a result of air filtration or other deposition mechanisms such as sedimentation:

$$a(t_i) = \frac{C_N(t_i)}{C_N(t_0)} \quad (3)$$

With $C_N(t_i)$ being the aerosol number concentration at a certain time t_i and $C_N(t_0)$ the aerosol number concentration in the room bevor air filtration was switched on. If $a(t_i)$ is multiplied with $f(t_i)$ derived from CO_2 concentration, Equation (4) gives the reproductive number including the influence of aerosol measurement:

$$R_{A0} = (n-1)\left[1 - \exp\left(-\frac{\overline{fa}qt}{n}\right)\right] \quad (4)$$

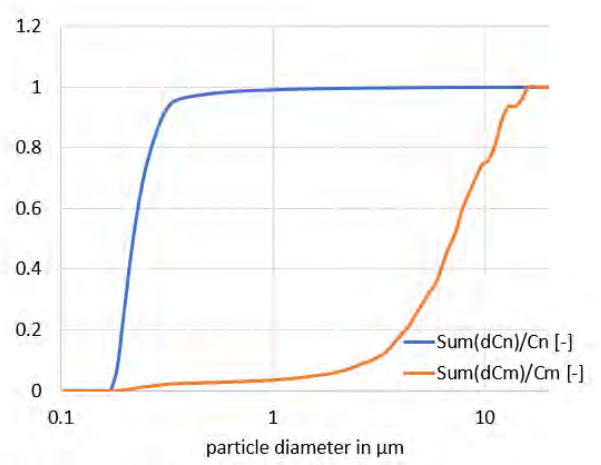

Figure 1: exemplary cumulative number distribution (blue) and mass distribution (orange) of indoor aerosol measured with AQ Guard in a classroom during class

It is essential that aerosol number concentration is chosen to evaluate aerosol concentration decrease and not aerosol mass concentration (known for example from ambient fine dust monitoring). The reason for this is that the quantum generation rate q in Equation (1) is a number-based measure of inhaled infectious

aerosol particles. A sensor for aerosol mass concentration will give a rather poor estimate of aerosol influence on infection risk. Figure 1 illustrates that for mass-based aerosol concentration particles >1µm make the most contribution and particles below 1µm are more or less neglectable. For the number-based aerosol concentration it is the other way around. So, aerosol mass concentration makes a very bad estimate for aerosol number concentration, especially with respect to exhaled aerosols sizes being around 0.3 µm (Schwarz (2012)).

Measurement technique and importance of lower cut-off

The measurement device used in this study to evaluate infection risk is the AQ Guard from Palas. The AQ Guard combines high accuracy optical aerosol spectrometer with an NDIR CO_2 sensor. The optical aerosol spectrometer of the AQ Guard has a lower cut-off at 0.175 µm.

The lower cutoff of the aerosol spectrometer is especially important regarding size distribution of the potential infectious aerosol. In Figure 2, the cut-off curve of AQ Guard and an exemplary cut-off curve of an OPC with 0.5 µm lower cut-off (typical for cleanroom counters) is shown together with a mean size distribution of exhaled aerosol (median of 0.3 µm and standard deviation of 1,78 from Schwarz, K. (2012)). The OPC will measure only 35% of the exhaled aerosol concentration due to being blind over a large range of the exhaled aerosol size spectra, while AQ Guard with a lower cut-off at 0,175 µm is able to see 87% of the exhaled aerosol concentration.

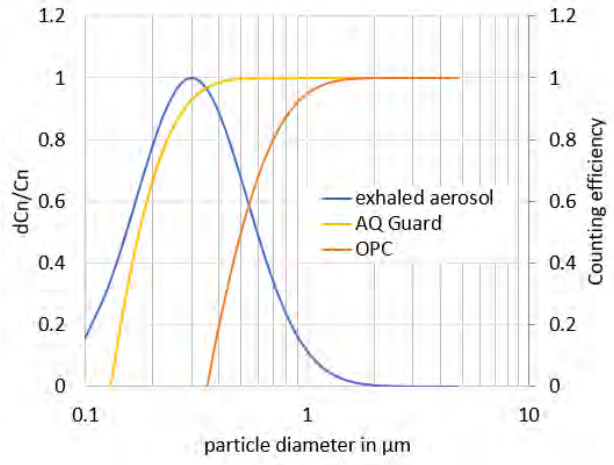

Figure 2: exemplary exhaled aerosol size distribution (blue) and counting efficiency curve of AQ Guard with lower cut-off at 0.175 µm (yellow) and exemplary OPC with lower cut-off at 0.5 µm (orange)

Lower cut-off is also important when it comes to evaluating the used air filtration device regarding filtration efficiency of potential infectious aerosol. Figure 3 shows two filter efficiency curves of HEPA filter measured with Palas Nano Plus filter test rig. The filter efficiency depends highly on particle size. The MPPS (most penetration particle size), meaning the particle size where the filter has the lowest efficiency, for this filter is around 0.2 µm, which very close to the expected median of exhaled aerosol size. For bigger particles, the filter is much more efficient. So evaluating the filter based on measurements of much bigger particles only, as a OPC with high cut-off would do, will overestimate the effect the filter has on reducing potential infectious aerosols and thus underestimating infection risk.

Also, when comparing different air filtration devices regarding reducing infection risk, it is essential to use an aerosol spectrometer that measures in the size range of exhaled aerosol. Because as can be seen in Figure 3, the largest difference in filtration efficiency between the filters is found around the MPPS the deviation gets smaller for bigger particle sizes. That means comparing the filter efficiency only for bigger particles will lead to the wrong conclusions.

RESULTS

To measure the infection risk in a real situation, classrooms in a public school were chosen. They provided a good situation to test infection risk measurements because of repeatable conditions such as occupation level, and duration of occupation as well as standardized airing habits (mandatory, 5-10 min airing every 20 min). In each room, the device was placed in a corner of the room away from the windows or the door to simulate the worst case for a student sitting in the most unfavorable place regarding fresh air supply. Also at least 2 m distance was kept to the next students to measure the level of CO2 and Aerosols distributed in the room, as the aim was to measure airborne transmission and not direct infection from one person to the next closest one.

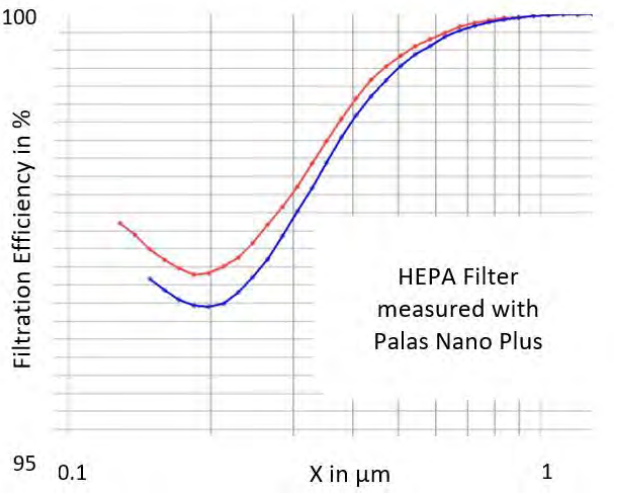

Figure 3: Filter efficiency curves of two HEPA filters measured with a Palas Nano Plus Filter test rig

Real situation infection risk measurement

Infection risk was measured in 9 different rooms with different occupation levels and conditions to air and with and without air filtration. Figure 4 shows an exemplary time chart of CO_2 and aerosol concentration (in the following referred to as Cn) over 45 min period and the resulting evolution of reductive number calculated according to Equation (1) (for CO_2 only) and Equation (4) (CO_2 and Cn influence).

The increase of CO_2 in the periods with closed windows is almost linear. Parallel to that, the reproductive number based on CO_2 only, shows an exponential increase during that time, too. When the windows are opened, the CO_2 concentration drops quickly and reaches start level again after the 5 minutes airing period. The reproductive number on the other hand, does not drop but only increases less steep. This is because the reproductive number can never drop as it represents the secondary infections based on prior inhaled infectious aerosols and airing can only prevent future secondary infections.
Cn on the contrary shows the opposite behavior, falling when windows are closed and rising during airing. The reason for this is that in environments with little activity, Cn falls due to natural deposition of particles like for example sedimentation. And also, during breathing the air is filtered in the respiratory tract. Nevertheless, if we compare the reproductive number with and without influence of Cn, effect for cases without air filtering device is very little.

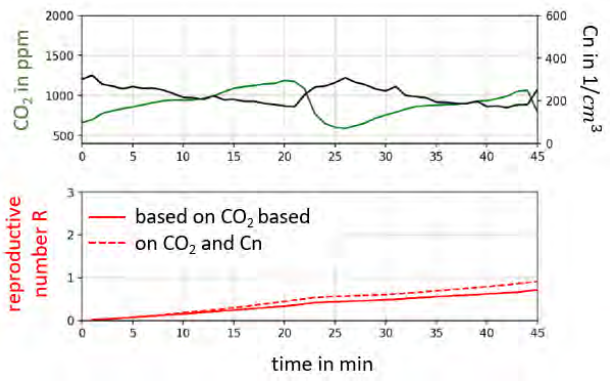

Figure 4: Exemplary curve of CO2 and aerosol concentration (a) and resulting reproductive number without and with influence of aerosol concentration (b) over time. No air purifier was used.

On average, the influence of Cn on reproductive number for all cases without air filtration was 20%. Figure 6 shows the measurements in of a school lesson with air filtering device running (Wolf AirPurifier equipped with HEPA H14 filter and set to an air exchange rate of 4 to 6 /h). Decrease of Cn as well as the difference between reproductive number without and with influence of Cn are significant. Calculating the infection risk only based on CO_2 would overestimate the infection risk by 75 % in this specific case, and on average 60%. This means estimating the real infection risk based on CO_2 measurement only will overestimate the real infection risk and airing needs. Accordingly, by including accurate measurements of Cn into the calculation of infection risk, the need for fresh air supply can be reduced which especially in winter saves heating costs.

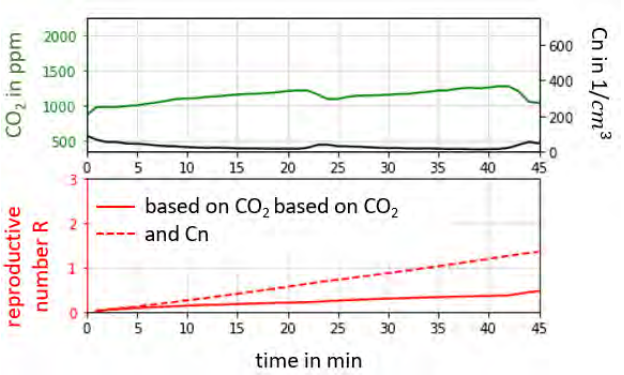

Figure 5: : Exemplary curve of CO_2 and aerosol concentration (a) and resulting reproductive number without and with influence of aerosol concentration (b) over time. Air purifier was used (Wolf AirPurifier).

Figure 6 shows the reproductive number at the end of each school lesson over the occupation (students per cbm room) for all the measurements. As expected, the reproductive number increases with the occupation. However, there are huge differences between the individual rooms. For example, in room 5 reproductive numbers are much lower than in room 9, although the occupation in room 9 is even less. Looking at the different rooms, room 5 has much bigger and more windows, so this outcome is not much of a surprise. For some rooms large scattering of reproductive number can be observed. This is mainly because boundary conditions such as initial CO_2 concentrations could not kept constant for all the school lessons, and it was also difficult to strictly follow the airing guidelines during ongoing school operation.

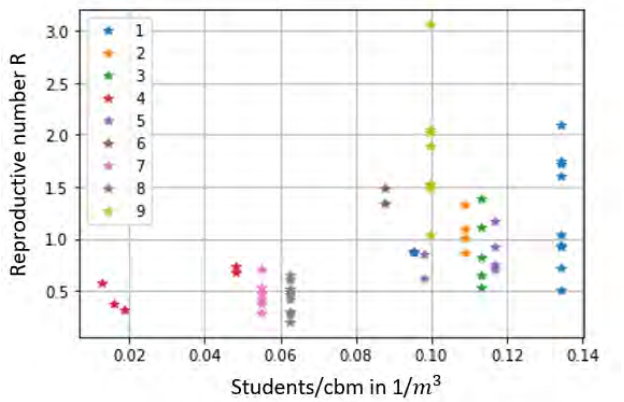

Figure 6: Reproductive number at end of one school lesson over classroom occupation.

The outcome of the infection risk measurements shown here is that infection risk and the success of airing is highly depending on the individual room. Thus, general guidelines such as those utilized in the observed schools, cannot assure safe indoor air quality.

In fact, measurements of real infection risk are needed to determine effective airing strategies.

Standardized procedure to evaluate indoor infection risk

As measurements of real infection risk involve rather complex and cost intensive measurement technique, it is not feasible to supply all rooms in question with an individual measurement device. Also, without knowing the infection risk, conducting experiments with people in the room can jeopardize their health, especially in the pandemic. Furthermore, different strategies (airing habits, air purifier, different settings of air filter system) shall be evaluated and compared. Therefore, a standardized and repeatable procedure to quantify infection risk in the best case without occupation is necessary to ensure healthy indoor environments.

Figure 7 shows an exemplary setup to evaluate a room regarding infection risk proposed by the authors. To determine the influence of aerosol on infection risk an aerosol generator is needed generating aerosol in the relevant size range of exhaled aerosol. In another corner away from the aerosol generator, the aerosol spectrometer is located. It measures the aerosol concentration of the aerosol equally distributed in the room. At the start of the procedure, the room is filled with aerosol from the aerosol generator, elevating the aerosol concentration way over normal indoor air level. After that the aerosol generator is switched off and the evaluation time span begins. This time span should represent a normal utilization scenario of the room including the airing or air filtration attempts to investigate. At the end of the procedure, the impact on aerosol concentration can be derived from the measurement data. Results for experiments using a similar procedure to evaluate the use of air filtration devices in classrooms can be found in the report from Szabadi et. al. (2020). However, to estimate the infection risk according to Equation (4), an CO_2 increase comparable to the utilization scenario or is needed. Accordingly, the setup can eighter be extended with people in the room or CO_2 from e.g. portable CO_2 bottle as source.

CONCLUSION

The authors have shown that calculation of infection risk based on CO_2 as a proxy for exhaled aerosols is limited to situations where no major changes in aerosol concentrations are expected. However, when an effort is made to reduce airborne infection risk in closed spaces by reducing aerosol concentration (e.g. with an air filtration device), aerosol concentration needs to be included into the calculation.

The results of measurements of indoor air quality in schools during school lessons have shown, that well-known equations from literature based on CO_2 only overestimate the infection risk (represented by reproductive number) by 20% in cases without active air filtration and by 60 % when an air filtration device was used.

The results show that aerosol concentration cannot be neglected when determining risk for airborne transmission of infectious diseases such as SARS-CoV-2 or influenza. Furthermore, indoor air quality must also focus on aerosol number concentration and not only particulate matter because the potential infectious aerosol consists of particles with a diameter around 0.3 µm and therefore hardly contributes to the mass-based particulate matter.

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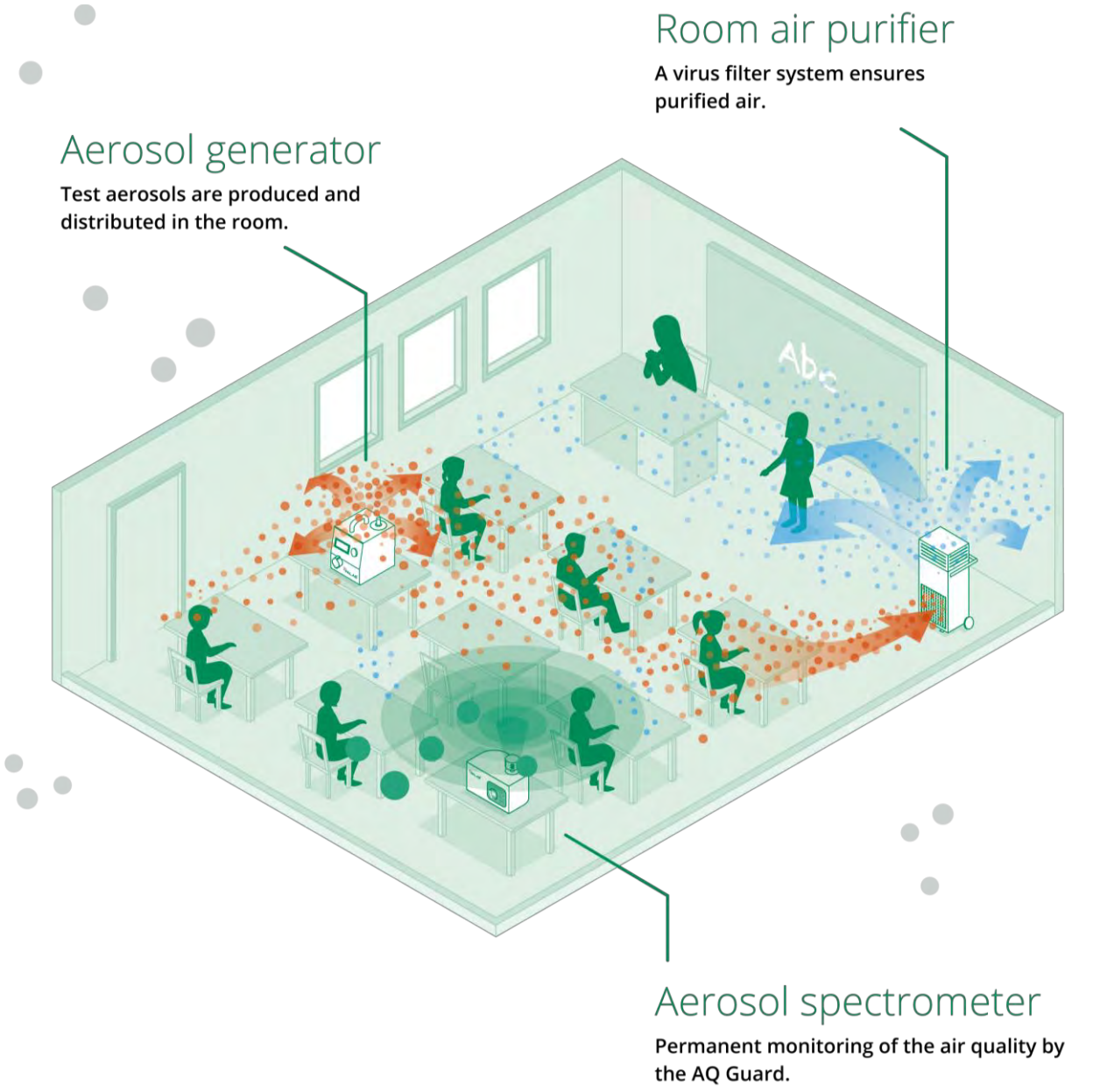

Figure 7: Exemplary setup to use for standard procedure to evaluate rooms regarding infection risk