Use of Portable Air Purification Systems to Eliminate Aerosol Particles from Patient Rooms

Dominic Dellweg1,2*, Gerhard Scheuch3, Thomas Voshaar4, Dieter Köhler1

1 Kloster Grafschaft, 57392 Schmallenberg, Germany
2 Philipps Universität Marburg, 35043 Marburg, Germany
3 GS Bio-Inhalation GmbH, Headquarters & Logistics, 35285 Gemünden, Germany
4 Bethanien Krankenhaus Moers, 47441 Moers, Germany

ABSTRACT

SARS-CoV-2 is mainly transmitted via airborne aerosols. We determined the efficacy of two different indoor air-purification systems and compared them to conventional measures of room ventilation. Radioactive particles with a mass median aerodynamic diameter of $0.6 \pm 0.4 \mu m$ were nebulized from the head position of a simulated patient inside a 38 m$^3$ measuring room. Air samples were drawn using an artificial lung from outside the room from the head and belly position of the simulated patient. The radioactivity from these air samples was determined in % of the minute-by-minute release of aerosol by the simulated patient. The samples were taken with the windows closed, with the windows open and with two different air purification systems in different locations. Opening the windows while the fan was working did not reduce the cumulative mass of sampled particles during ongoing nebulization. Only the more powerful air purifier was able to decrease cumulative sampled radioactivity almost to zero when positioned close to the emitting particle source. We observed air-turbulences caused by the air intake of the air purifier resulting in regional particle concentration peaks. Measurements and calculations demonstrate that indoor air purification systems can be effective measures to eliminate airborne particles. The air cleaning capacity of the system must be matched to the room size and the air intake of the units should be positioned close to the particle source.

Keywords: Coronavirus, Sars-CoV-2, COVID, Air purification system, Aerosol, Airborne particles, Virus transmission

1 INTRODUCTION

The link between the SARS-CoV-2 virus and a disease which is now named COVID-19 was first established at the end of 2019 (Zhu et al., 2020). A discussion about the transmission path of the virus has flared up since then (Bahl et al., 2020; Jayaweera et al., 2020; Lewis, 2020). It is generally accepted, that the virus is a part of particles during the transmission process from host to host. For historical reasons transmission has been classified either as droplet- or airborne-transmitted and the cutoff in-between these categories was thought to be somewhere around a particle size of 5 µm (Deverick, 2018). The sedimentation rate of particles depends on size, density, shape, and the air circulation and convective air movements (Scheuch, 2020). Particle properties change rapidly once a particle has left the human respiratory system. Dependent on temperature and humidity of the environment particles shrink rapidly and change their physical properties (Xie et al., 2007; Pöhlker et al., 2021). The use of a cutoff value to differentiate between airborne and ballistic particles or droplets therefore not satisfy the real dynamic properties of exhaled particles (Scheuch, 2020). Evidence suggests, that aerosol-particles play a major role in the spread of the Sars-CoV-2 virus (Chia et al., 2020; Liu et al., 2020) and that more than 99% of infections occur in indoor settings (McGreedy, 2021; Qian et al., 2021). The infective dose of the SARS-CoV-2 virus is currently thought to be somewhere around 300 viral copies (Basu, 2021). The transmission risk
from an infected to a healthy person depends on the following factors: Infectious particle emission rate, room size, exposure time, minute ventilation of the healthy person and air exchange rate respective air cleaner efficacy. Air filtration by using air purification systems have been proposed by some authors (Christopherson et al., 2020; Nazarenko, 2020), and have been officially recommended by the WHO (WHO, 2021). Investigation published before the spread of the corona virus had mainly focused on the use of air cleaners for the reduction of ubiquitous particulate matter (Brehmer et al., 2019; Cox et al., 2018; Fermo et al., 2020; Kyung et al., 2020; Park et al., 2020; Stauffer et al., 2020; Ward et al., 2005). More recent research has focused on elimination of human emitted particles as well as simulated particle spectra (Curtius et al., 2021; Szabadi et al., 2022; Burgmann and Janoske, 2021; Küpper et al., 2019). Due to the high numbers of patients suffering from COVID-19 the majority of patients are treated outside of special infection isolation rooms with built-in high efficiency particulate air (HEPA) filtration systems.

The rationale of our investigation was to measure the effectivity of commercially available portable air filter systems in eliminating small airborne particles emitted from a simulated patient and to compare it to conventional measures of room ventilation such as opening a window and using a fan. In our simulation we intended to measure the proportion aerosol particles that is inhaled by a health care worker caring for an infected patient who is emitting infectious particles during different settings of air filtration and air exchange. Ultimately, the goal is to determine the cumulative inhaled particle dose of a health care worker in a typical working position in relation to the patient’s minute-by-minute particle output.

## 2 METHODS

The experiments were carried out in a single room with the dimensions 4.9 m length, 3.2 m width and 2.4 m height (volume 38 m³) with a window measuring 1.2 m², which is comparable to the size of a single intensive care unit (ICU) room (Fig. 1).
The experimental setup was positioned around a standard size ICU bed. Particle release by a patient was simulated by nebulization with a jet nebulizer, positioned at the head of the bed at a height of 1 m above floor level. We nebulized 0.9 isotonic saline containing 150 MBq $^{99m}$Tc-DTPA ($^{99m}$Tc-diethylenetriamine pentaacetae (DTPA) per ml by means of a Pari LC Sprint Star nebulizer (Pari, Starnberg, Germany) in a 30 degree upward direction, which corresponds to the respiratory flow of a patient with 45 degree upper body position (Dellweg et al., 2021). The nebulizer output rate equals 450 mg min$^{-1}$. The aerosol had a mass median aerodynamic diameter (MMAD) of 2.8 $\pm$ 2 $\mu$m. These particles dry within milliseconds resulting in particles of 0.6 $\pm$ 0.4 $\mu$m MMAD (Haddrell et al., 2014; Maurer et al., 2020). Inhalation of the particles by a healthcare professional was simulated at two sampling sites with a height of 1.2 m above the ground at the head (sampling position 1) end around the belly of the patient (sampling position 2), simulating a health care worker who is leaning forward during patient care.

We used a two chamber Michigan lung (dual adult test lung model 5600i, Michigan Instruments, Kentwood, MI, USA) to simulate breathing. The test lung was positioned outside the room. The chambers of the lung were blocked with the built-in lock bar to assure equal tidal volumes of either chamber. Two antistatic tubes with a volume of 750 mL each, which were passed through holes in the door connected the sampling position 1 and 2 with Michigan Lung. We collected the radioactive particles outside the room with two filters each (Iso-Gard #19212, Teleflex Medical GmbH, Fellbach, Germany) which were mounted in-between the tubing system and the test-lung. Preparatory experiments confirmed a filtration efficacy of 99.5% (pass ration 0.5%) of two cascaded filters. Breathing by the health care worker at the bedside was simulated by six manual motions of the test lung chambers to the 1.75-liter mark on the built-in scale within 30 second’s time. After subtraction of the volume of the antistatic tubes this relates to a tidal volume of one liter and a respiratory rate of 12 breaths per minute, which is a representative minute ventilation of a nurse physically working at the bedside. Samples were drawn prior to the experiment and then every 2 minutes during the 30 minutes lasting experiments. We stopped aerosol nebulization after 20 minutes, but continued to collect the airborne particle in order to simulate a situation equivalent to intubation of the patient or non-invasive ventilation using viral filters on the exhalation port.

We determined the absolute particle output of the nebulizer during a 30 second nebulization period prior to every test run. In order to avoid any significant resistance to the outflow of the nebulizer, eight filters had to be connected in parallel configuration. The 30 seconds nebulization mimics the minute ventilation respectively the amount of exhaled viruses of the patient within 1 minute and served as a reference point. With this information we are able to determine the cumulative inhaled dose of a simulated healthcare worker in relation to the dose that a patient would emit within one minute. Date on emitted particles in humans during breathing and speech have been published (Asadi et al., 2019; Morawska and Buonanno, 2021) and it is known, that particle number in human exhalate is increasing during infection (Edwards et al., 2021). With knowledge of the number of viral copies required to cause an infection and the dose of exhaled viruses in a given patient (Leung et al., 2020) one can determine the time to infection with the help of our cumulative curves.

The natural half-life of $^{99m}$Tc is 6.01 hours. For all measuring points, the natural decay rate of the isotope was calculated out. For radiation protection reasons, we decided against using an isotope with a longer half-life. The use of $^{99m}$Tc, in combination with ventilation measures overnight, made it possible to conduct one daily measurement, whereby the radioactivity at the start of the measurement always corresponded to the background activity of the natural environment.

During the test series with the air purifiers, their air inlet was always facing the bed. Because we saw in preliminary experiments sometimes unexpected peaks of aerosols, we visualized the aerosol with tobacco smoke from a pipe. Therefore, a tobacco pipe was used in reverse since tobacco smoke is known to have the same particle size compared to human aerosols (Hinds, 1978; Anderson et al., 1989). Compressor air was blown into the bowl of the pipe. The tobacco pipe was placed at the same place as the nebulizer. The pipe smoke was recorded with a video camera.

### 2.1 Tested Devices

1. Fan (Trotec, D-52525 Heinsberg, Germany. Type TDS 10) ventilation rate 300 m$^3$ h$^{-1}$) which was positioned behind the patient’s head with the airflow directed towards the window. The
ventilator was deliberately not positioned directly in front of the window to avoid circulatory short circuits.
2. Air purification system P (Phillips, D-2235 Hamburg, Germany.) Type: AC2889/10 Clean air delivery rate (CADR) 330 m³ hour⁻¹ with HEPA Filter (99.97% efficacy for 0.3 µm particles).
3. Air purification system T (Trotec, D-52525 Heinsberg, Germany.) Type TAC V+ Clean air delivery rate (CADR) 1000 m³ hour⁻¹ with HEPA filter (99.995% efficacy for 0.3 µm particles).
Every device could be activated and deactivated from outside the room by means of a remote-control system.

2.2 Measurement of Radioactivity
After every test-run we positioned the filters under a Gamma camera (ECAM Scintron, Medical imaging electronics GmbH, Seth, Germany) and radioactivity was counted for one minute. Regions of interest (ROI’s) were placed around the radioactive spots. A third ROI apart from the filter spots measured background activity. Activity was measured in total counts per minute and the half-life of ⁹⁹ᵐTc has been corrected.

2.3 Test Runs
1. 20-minute nebulization into the closed room to measure the natural behavior and of the radioactive aerosol, without any intervention.
2. 20-minute nebulization while the window was completely open and the fan was working on full power.
3. 20-minute nebulization with either air cleaner P or T positioned on the ground at the foot of the bed while the window was closed and the fan was not operating.
4. 20-minute nebulization with either air cleaner P or T positioned on the ground at the head of the bed while the window was closed and the fan was not operating.
5. 20-minute nebulization with either air cleaner P or T positioned at bed level at the head of the bed while the window was closed and the fan was not operating.

In order to visualize the motion of the aerosol plume, we blew smoke particles from a pipe from the head position of the bed. Tobacco smoke has a particle spectrum comparable to the radioactive aerosol we applied (Hinds, 1978; Anderson et al., 1989).
Every test run was conducted three times. Data are presented as means with 95% confidence intervals.

3 RESULTS AND DISCUSSION
The natural decline of radioactive particles from the two sampling positions (Fig. 1) without any further intervention is shown in Fig. 2 including additional samples that were drawn at 60, 150 and 300 minutes to determine the natural decline of radioactive aerosols over a 5-hour period. Since the radioactive decay of the isotopes was calculated out, the decrease in isotopes in the drawn samples represents the natural dilution and deposition of the aerosols in the room. A fifty per cent drop in particle concentrations was achieved after 200 minutes. It was approximately the same for both sampling positions. Operating a fan while the 1.2 m² window is open does not clear remarkably particles from the room while the nebulization is ongoing as shown by the increasing cumulative inhaled dose up to minute 20 (Fig. 2 lower panels). However, when the nebulization is stopped, particle concentration starts to decline, which is indicated by smaller inclines of the curve in Fig. 2 from the twentieth minute on (Fig. 2 lower panels).

The course of the cumulative inhaled particle dose when operating the air cleaners one meter apart from the foot of the bed is shown in Fig. 3. Please note the differences in the Y-scale of upper and lower panels of Fig. 3.

Positioning of the two air cleaners at the head of the bed on floor- and bed-height respectively is shown in Figs. 4 and 5.

Fig. 6 shows deviation of the aerosol plume caused by the air-turbulences from air cleaner T when positioned at the foot of the bed.

The major finding of our investigation is, that air cleaners can be very effective when operated close to the aerosol source, in this case at the head position of the bed. The air delivery rate of
Fig. 2. Upper panels show the natural decline of the radioactivity in the room while the windows are closed. The lower panels illustrate the cumulative inhaled radioactivity in % of the nebulizer output in 1/2 minute, e.g., reflecting the exhaled particle load of 1 minute during normal breathing, while the window is open and the fan is operating. NOT = nebulizer operating time (20 minutes); Error bars: 95% CI.

the air cleaner however appears to be the other important factor for particle clearance especially if the aerosol source is constantly emitting particles.

The air intake rate of air cleaner T however appeared to impact the aerosol spreading when positioned at the foot of the bed. The measurements were more variable as shown by the wider interval of confidence especially with the more powerful cleaner T (Fig. 3). This variability is most likely explained by air movement and turbulences caused by the air intake of the cleaner as visualized in our smoke particle experiment (Fig. 6). However, working between emitting source and air-cleaner-inlet might even increase the inhaled dose as shown in Fig. 3. Depending on the position of the same air purifier, a health care worker can inhale between less than one and up to 35 per cent of the particle dose delivered by a patient in one minute (Figs. 3 and 5, lower panels). Pöhlker et al. (2021) distinguish between short-range and long-range infection risks. In general, heavy particles which are generated in the upper respiratory tract and the mouth during talking, coughing or sneezing have a higher range after acceleration due to their higher mass. However, they also have a higher sedimentation rate and sink faster while smaller particles from the lower respiratory tract remain airborne for longer times. The measurements we carried out took place in the short-range with a particle spectrum such as that produced during normal breathing. Szabadi et al. (2022) showed, that real-room scenarios show a slower particle decay than the predicted ones assuming ideal mixing of the indoor air as suggested by a stirred tank reactor model. Burgmann and Janoske (2021) showed, that movement of people within a room might impact local particle concentrations and Küpper et al. (2019) showed similar aerosol decay rates, when cleaners were placed in similar positions but not for example, when placed under a desk. Since our room did not have any additional furniture besides the patient bed which was positioned in the middle of the room we have to assume that aerosol distribution respective the mixing level was mainly influenced by outlet of the nebulizer and the airstream of the ventilator.
Fig. 3. Cleaners located on the ground and at the foot of the bed. NOT = nebulizer operating time (20 minutes); Error bars: 95% CI.

Fig. 4. Cleaners on the ground at the head of the bed. NOT = nebulizer operating time (20 minutes); Error bars: 95% CI.
Current recommendations for airborne precautions propose twelve air exchanges per hour (ACH) for infection isolation rooms (Medical Advisory Secretariat, 2005; Jensen et al., 2005). Built-in air cleaning systems in infection isolation rooms usually work by air replacement. If the air inside a closed room however is cleaned by an indoor air cleaner, air mixing has to be taken into account with an additional factor of 1.5 resulting in $1.5 \times 12 = 18$ ACH (Medical Advisory Secretariat, 2005).

The room in our experimental setup had a size of 38 m$^3$. This would require an ACH of 684 ($38 \times 12 \times 1.5$) m$^3$ h$^{-1}$ of air cleaning capacity for a room of this size and if an indoor air cleaning system is installed. The capacity of the investigated air cleaners was 330 m$^3$ h$^{-1}$ (cleaner P) and 1000 m$^3$ h$^{-1}$ (cleaner T) respectively which explains the observed difference in efficacy.
Previous recommendations have already pointed out, that the air inlet of air purification systems should be located as close as possible to the infectious source itself (U.S. EPA, 2008). The latter is easy to be realized in hospital rooms where the patient is the suspected source of infection in rooms with no or ineffective installed air cleaning systems. We have shown that this is very effective with powerful air cleaners. However, the air cleaning systems up to now have the air inlet at the ground. Therefore, the air cleaning system in our experiment had to be placed in an elevated position. The importance of position of the air cleaner in relation to the particle emitting source have been highlighted by previous investigations (Chen et al., 2010). Aerosols from the human respiratory tract are warmer than ambient air and therefor will rise. However, this was not taken into account in our experiments, but the exhaled airstream in the nearfield of an emitting person is mainly determined by the direction of the exhaled airflow rather than by the uprise due to temperature differences (Dellweg et al., 2021). Having the air inlet at the ceiling of a room would support this natural flow. The inlet of air cleaners could be connected to tubing systems which connects to one or more suction ports, located at the ceiling of the room. This constellation would prevent horizontal airstreams which could carry aerosols from subject to subject.

The use of air purification systems is of course not limited to healthcare settings but could be applied to any indoor scenario where people assemble.

4 CONCLUSIONS

Our results imply, that portable air cleaners might play an important role in decontaminating rooms from particles, however beyond room size, the delivery rate of the air cleaner and the spatial arrangement of the aerosol source and the cleaner inlet appear to be the major determinants of the clearing rate but also of aerosol distribution inside the room. The use of air purification systems does not allow to refrain from other precaution measures such as wearing face masks and other personal protection equipment where indicated.

ADDITIONAL INFORMATION

Conflict of Interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement
Raw data of our investigation are available on the Mendeley data server: https://data.mendeley.com/research-data/?search=dellweg

SUPPLEMENTARY MATERIAL

Supplementary material for this article can be found in the online version at https://doi.org/10.4209/aaqr.210369

REFERENCES


