Science of the Total Environment 772 (2021) 144956

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Air filtration as a tool for the reduction of viral aerosols

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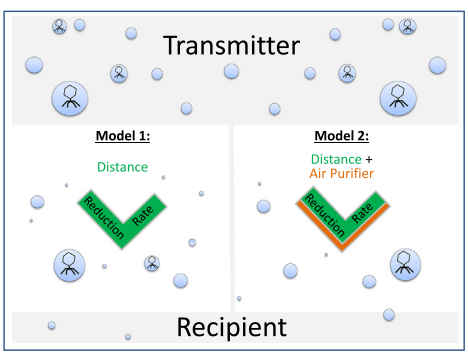
HIGHLIGHTS

- Use of bacteriophages is suitable to test air purification devices under experimental conditions.
- Using air purifiers with HEPA filters, a reduction of test viruses 99.997–99.999% can be achieved.
- The application of air purifiers is not able to stop direct transmission.
- Maintaining distance is an important risk-reducing factor for the transmission of viral aerosols.
- The use of mobile air purifiers cannot replace other safety measures already in implementation.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 5 November 2020
Received in revised form 2 December 2020
Accepted 31 December 2020
Available online 1 February 2021

Editor: Philip K. Hopke

Keywords:
Bacteriophages
Air purification
phiX174
COVID-19
Transmission

ABSTRACT

For testing the effectiveness of air purification devices in regard to the reduction of virus-containing aerosols, a test method involving test viruses has been lacking until now. The use of bacteriophages (phiX174 phages) is a method to test the efficiency of air purification devices under experimental conditions. Using air purifiers with a HEPA filter H14, a 4.6–6.1 Log reduction of test viruses can be achieved if bacteriophages are directly aerosolised into the air purifier, which corresponds to a reduction of 99.9974–99.9999%. Due to the complexity and individuality of air flow, an experimental approach was used in which all outside influences were minimised. The experimental setup was practical and chosen to project a scenario of direct transmission by an emitting source to a recipient. The experiments were performed with and without the air purifier at a distance of 0.75 m and 1.5 m each. Using the air purifier at a setting of 1000 m^3/h, the concentration of the phiX174 phages in the air could be reduced by 2.86 Log (mean value). Nevertheless, the experiments without the air purifier showed a similar reduction rate of 2.61 Log (mean value) after 35 min. The concentration of phiX174 phages in the air could be additionally reduced up to 1 log step (maximum value) by the use of the air purifier in comparison to the experiments without. Distance was shown to be an important factor for risk reduction.

1. Introduction

In regard to the ongoing SARS-CoV-2 pandemic, the significance of aerosols for SARS-CoV-2 transmission and the role of adequate indoor air quality are currently being discussed. According to the current state of research, SARS-CoV-2 is transmitted primarily via droplets that are produced when breathing, speaking, singing, coughing, or sneezing and are exhaled and inhaled through the air (Jayaweera et al., 2020; Morawska and Cao, 2020; Zhang et al., 2020; Lu et al., 2020). Aerosols containing viable SARS-CoV-2 particles could be detected 4.8 m away from an infected patient in a hospital ward (Lednicky et al., 2020).

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https://doi.org/10.1016/j.scitotenv.2021.144956
0048-9697/

Mouth and nose covers or masks are generally recognised as control measures to reduce the direct risk of infection. These masks offer good protection of others by preventing or reducing the emission of viruses into the air. The amount of particle emission during normal human speech is positively correlated with the loudness (amplitude) of vocalisation, ranging from approximately 1 to 50 particles per second, which corresponds to 0.06 to 3 particles per cm^3 (Asadi et al., 2019). Despite their small size, however, these particles are sufficiently large to carry a variety of respiratory pathogens, such as the influenza virus (100 nm to 1 μm) (Alford et al., 1966).

Respiratory particles can be classified as droplets or aerosols based on particle size and aerodynamic diameter (Hinds, 2012). Fluid droplets from the cough or sneeze of an infected patient are typically 5 μm or larger (Elias and Bar-Yam, 2020). Both droplets and aerosols are generated during coughing, sneezing, talking, or exhaling, but large droplets settle quickly, whereas small aerosols can remain airborne and may transport over longer distances by airflow (Gralton et al., 2011; Wells, 1934). Therefore, unlike larger droplets, contaminated aerosols can theoretically pose an infection risk over a greater distance; although, it should be noted that most aerosol transmission is likely to occur at close range because of dilution and inactivation of viruses over longer periods and greater distances. Small aerosols containing viruses are more likely to be deeply inhaled into the lung and may cause infection in the alveolar tissues of the lower respiratory tract, whereas large droplets may be trapped in the upper airways (Hatch, 1942). The World Health Organization (WHO) and the U.S. Centers for Disease Control and Prevention (CDC) consider disease transmission with particles larger than 5 μm as droplet transmission and with particles of 5 μm in size/diameter or less as aerosol transmission (Cole and Cook, 1998; Siegel et al., 2007; WHO, 2007). The number of droplets remaining airborne depends not just on their size but also on turbulence and speed of the drifting air. In calm air, large droplets (carrying the biggest load of viruses) will sediment faster than in turbulent air (Duguid, 1946; Tellier, 2006). It is unclear how many particles are being emitted by an infected person, and no clear infection dose of SARS-CoV-2 has been described. Jayaweera et al. (2020) states that there is no discernible evidence regarding infection dose, whereas Beggs (2020) speculates that a few hundred virus particles are enough to infect a susceptible host. Asadi et al. (2019) found that 4 particles per second were emitted by a person speaking in a loud voice, and studies on super-emitters have shown that 30% of emitted particles (<5 μm) contain potentially infectious virus particles (Lelieveld et al., 2020).

There are only a few epidemiological publications in which transmission by aerosols seems to be verified by whole genome sequencing (Guenther et al., 2020) under specialised conditions in a meat processing environment. However, the percentage of transmission by aerosols versus droplets in context with related risk factors has remained unknown until now. The use of recirculated air in closed poorly ventilated rooms with a large number of people performing hard physical work is likely to be a risky situation (Guenther et al., 2020).

While larger droplets are effectively hindered by using simple mouth and nose covers, small droplets may get into the outside air through gaps at the edge of the mouth and nose covers. Since larger droplets can statistically transport more viruses than small droplets, this effect is significant in processes that primarily produce large droplets (coughing, sneezing) (Kähler and Hain, 2020). These coverings only provide effective protection if a safe distance (at least 1.5 m) can also be maintained. Due to the physical factors, small droplets initially remain in the vicinity of the head. The short-term spread of droplets by speaking, singing, coughing, or sneezing while wearing a mouth and nose cover is severely limited, and the direct risk of infection is reduced (Wells and Wells, 1936). An indirect infection through inhaling of infectious aerosols, which may accumulate in the room over time, while not wearing a mouth and nose cover is possible (Kähler and Hain, 2020). This path of infection can only occur indoors if the volume of the room is small in relation to the number of people infected. In large rooms such as churches, even many infected persons will not be able to generate an infectious viral dose. It is clear that an indirect infection cannot be prevented by maintaining safe distances from infected persons, since the air in the room may be filled with viral-laden aerosols (Geddes, 2020; Stadnytskyi et al., 2020). Under these conditions, protection against infection can only be achieved by a short duration of stay or technical aids.

Methods for cleaning possibly contaminated air are versatile; techniques such as free ventilation by opening windows, technical air filtration using filters, and non-thermal plasma treatment are currently being discussed (Curtius et al., 2020; Tysiąc-Miśta et al., 2020; Wang et al., 2019). The successful application of all these methods is currently only theoretically assumed. Except for a few studies, epidemiological evidence is still missing. Filters that reliably separate aerosols with a diameter of less than 1 μm do exist but are often part of large technical ventilation systems. Whether free ventilation using windows may not be applicable in winter without wasting energy and endangering people's health and well-being is a current topic of discussion. An additional topic of scientific and political discussion is whether mobile air purifiers are suitable for significantly reducing of viral aerosols in a room by reducing the need for free ventilation. Different publications have shown the performance of different air purifiers by using standardised particle clouds, a uniform distribution of particles in the room, and measuring the reduction of particles in the air (Kähler et al., 2020a, 2020b). Another study on air purifiers in a classroom situation used mainly physical particle measurements and extrapolated these findings on the purification of viral particles potentially contained in air particles (Curtius et al., 2020). The question, however, whether mobile air filtration could be a useful tool for the reduction of viral aerosols in the air remains unanswered.

Bacteriophages are often used as models for human-pathogenic viral aerosol studies (Turgeon et al., 2014). Bacterial viruses are not pathogens for humans. Their study does not require specialised biocontainment precautions, and they are easy to produce in large quantities (Gill and Hyman, 2010). Bacteriophages can be found with a high diversity of genetic and morphological properties. They have frequently been studied and used as surrogates for eukaryotic viruses (Lute et al., 2004). Bacteriophages, such as MS2, 6, and phiX174, have been explored as viral aerosol models (Verreault et al., 2008). Turgeon et al. (2014) tested five different bacteriophages and found that the RNA phage MS2 and the ssDNA phage phiX174 were the most suitable for aerosol formation and sampling due to their tenacity, whereas the phages PM2 could only be recovered in 3 out of 18 spiked samples. Culture-based methods are often used in studies in context with bacteriophages because using cultural methods in comparison with molecular methods (quantification of target genes by polymerase chain reaction, qPCR) of total viral particles collected by a sampler is more suitable for assessing the physical stress caused by aerosol formation and air sampling (Phillpotts et al., 2010). Turgeon et al. (2014) showed that the MS2 phages and phiX174 phages show the most similar recovery rates between culture-based methods and qPCR method. Because MS2 phages have been shown to be 7 to 10 times more resistant to aerosolisation, sampling, and UV light than a coronavirus (Walker et al., 2013), the one-Log-more-sensitive phiX174 phages were chosen for the experiments.

The goal of this study was to assess the capacity of mobile air purifiers to remove virus-containing aerosols using bacteriophages as a surrogate for SARS-CoV-2 and other human-pathogenic respiratory viruses.

2. Materials and methods

2.1. Laboratory strains

The bacteriophages used were the phages phiX174 of the family *Microviridae*. They have a small ssDNA genome packaged into a

small icosahedral protein shell, are unenveloped and 25 nm in size, and the bacterial host is *Escherichia coli* (Fiers and Sinsheimer, 1962). PhiX174 phages are bacterial viruses capable of infecting selected *E. coli* host strains (and related strains) by attaching to the bacterial cell wall. As a bacterial host, the strain *E. coli* ATCC 700078 was used, as determined in ISO 10705-2, 2002-02. Preparation of phiX174 and *E. coli* cultures was done according to ISO 10705-2, 2002-02 for the detection and enumeration of bacteriophages in water.

2.2. Detection of coliphages

The method ISO 10705-2, 2002-02 specifies the detection and enumeration of somatic coliphages (phiX174 phages) by incubating the sample with a suitable host strain. The method can be used for all types of water, sediments, and slurries, if necessary, after dilution. For the production of a fresh inoculation culture of *E. coli* (DSM 18455), 0.5 mL of the working culture was transferred to 50 mL of Modified Scholten's Agar (MSB) (ISO 10705-2, 2002-02) and incubated at 36 ± 2 °C in a shaking water bath (approximately 3–4 h) until the turbidity of the suspension corresponded to at least a bacterial density of approximately 10^8 per mL. A control of the *E. coli* concentration was performed by establishing a growth curve for the used *E. coli* strain. Ten millilitres of sample (for highly contaminated samples, 9 mL of sterile distilled water and 1 mL of sample or its dilution) was transferred to a sterile test tube (50 mL), and 1 mL of fresh inoculation culture of *E. coli* and 11 mL of double-concentrated MSA (ISO 10705-2, 2002-02) were added and immediately poured into 2 sterile petri dishes. A positive and negative sample was prepared for each examination procedure. All samples were incubated at 36 ± 2 °C for 18 ± 2 h. The results are given as Log10 of plaque forming units (pfu) per one cubic meter of air (m^3).

2.3. Aerosol formation and air sampling

Aerosol formation from a suspension of phiX174 phages was conducted using the inhalation device PARI Boy PARI LC SPRINT (Pari GmbH, Starnberg, Germany). Defined phiX174 phage suspensions with known concentrations of phages were aerosolised into the room. To determine the number of phiX174 phages in the air after aerosol formation, the air was collected and concentrated in a solution of 0.9% NaCl. The sampling with the biological air sampler Coriolis® μ is based on a cyclone-like operation; the air is sucked into a conical collecting vessel in a swirling motion. All substances and particles in the air are pulled against the wall of the vessel by a centrifugal force and separated from the air to be concentrated in a defined volume of 0.9% NaCl. In the described test series, 300 L of air per minute were collected.

The collection time was 5 min, so that a total of 1.5 m^3 air was collected (corresponding to 5% air in the room). All samples were analysed within 2 h after sampling. The described test method has been validated in the laboratory and meets the requirements for indoor air tests. All steps of analysis have been tested for individual recovery rates and detection limits.

2.4. Droplet sizes

The individual sizes of the produced droplets contained in the aerosol produced by the PARI LC SPRINT were measured using the particle counter PC220 (Trotec, Heinsberg, Germany). The sizes of the droplets contained in the surrounding air were determined directly at the outlet of the PARI LC SPRINT, corresponding distances of 0, 5, 10, 25, 50, 75, 100, and 150 cm from the aerosol emission. The ratios of the droplet sizes were calculated in regard to the total number of particles measured in 1 L of air.

2.5. Filter used

The air purifier used contained an H14 HEPA high-performance filter. According to EN 1822:2009, this type of filter should be able to reduce aerosol particles with a diameter of 0.1 to 0.3 μm by 99.995%. The device can be operated in different flow rates up to 1600 m^3/h. A clean zone area of 320 m^3 can be achieved with 5-fold air exchange per hour (manufacturer information). The air purifier was used at a flow rate of 1000 m^3/h. This corresponds to a 33-fold air exchange rate per hour in the test room (Fig. 1). Additionally, the decibel level was measured with setup options of 1600 m^3 and 1000 m^3 at a distance of 1 m from the air purifier using a BAPPU evo multimetre (Elk GmbH, Germany) for measurements of health relevant environmental characteristics such as decibel. The decibel was measured as a mean value over a period of 1 min (dB/min).

2.6. Experimental setup

Due to the complexity and individuality of air flow, an experimental approach was used in which most outside influence was reduced. The experimental setup was carefully considered for the assessment of the added value of the air filtration in a practical experimental setup. The room in which the experiments were conducted had an air volume of 30 m^3. All possible points for air supply (vents, doorways) were covered to minimise the air flow within the room. The room contained only the experimental equipment and the person performing the experiments, who only moved inside the room when necessary.

Internationally accepted regulation on the distance between 2 individuals for combat of the ongoing COVID-19 pandemic is 1.5 m. In this study, two distances between the emitting source (PARI LC SPRINT) and the recipient (Coriolis μ) were tested to determine the effect of distance as a tool to control the risk of infection (model 1). For the determination of phiX174 phage concentration depending on the distance of the emitting source and recipient, the experimental setup was carried out in two different spatial arrangements of the devices. In scenario 1, the distance between all 3 devices involved in the experiment was 1.5 m. In scenario 2, the distance between the Pari LC Sprint nebuliser and the Coriolis μ air sampler was reduced to 0.75 m. The suspension of phiX174 phages with a concentration of 10^6 to 10^9 pfu/mL was aerosolised using the PARI Boy PARI LC SPRINT (5 min operation time). The air sampling was conducted directly after aerosol formation with the Coriolis μ setup for 5 min, corresponding to 1.5 m^3 of air.

For the determination of phage concentration as a function of time at a distance of 1.5 m for all used devices (scenario 1), the phiX174 phages (10^6 to 10^9 pfu/mL) were nebulised for 5 min by the PARI Boy PARI LC SPRINT. Then, the concentration of the phages in the air was measured

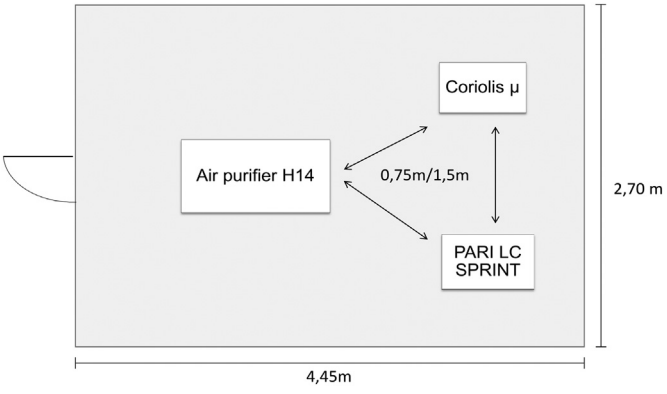

Fig. 1. Sketch of the test room (30.4 m^3). All possible places for air exchange were taped and plugged. One person performing the experiments was present in the room during the experiments. All movements in the room were reduced to a minimum.

by air sampling using the Coriolis μ (collection volume of 1.5 m^3) starting at 5 min after aerosol formation (5–10 min after emission) and again after 5 min for a period of 5 min (15–20 min after emission) up to 35–40 min after aerosol formation. Aerosol formation and collection of the air was performed at a height of 1.10 m each (person sitting). This experiment was conducted with and without the air purifier (flow rate of 1000 m^3/h) (model 2). In the experiments using the air purifier, the device was started directly after aerosol formation. In order to determine the influence of the air sampler Coriolis μ on the air purification in the room, the test setup "model 2" was repeated with only a Coriolis μ sampling at a time of 35 min after aerosol formation.

2.7. Retention of viral aerosols by air filtration

To test the performance of the HEPA H14 filter for the reduction of viruses in the aerosols, phiX174 phages (concentration of 10^6 pfu/mL) were nebulised directly into the intake of the air purifier, by putting the PARI LC SPRINT directly at the point of air intake. The air was sampled using the Coriolis μ directly at the exhaust over a period of 10 min starting directly with aerosol formation. The analysis was repeated using a larger distance, up to 1.5 m, between emitting source and purifier to allow the initial produced aerosols to shrink due to desiccation. The experiment was repeated five times. The individual reduction rates are given in decadic logarithmic values and in percentages.

3. Results

The initial experimental setup was chosen to be as similar as possible to a spreading event in a small, closed room, with as little as possible additional air exchange influences next to the tested air purifier. After testing the simple effects of distance on a possible transmission, further experiments were conducted with the universally acknowledged distance of 1.5 m. The filtration rate of 1000 m^3/h was chosen due to the decibel measured at the 2 tested operation modes of the air purifier. The average decibel for the highest operation mode (1600 m^3/h) was 61.9 dB/min, whereas the operation mode of 1000 m^3/h showed less noise pollution of 54.6 dB/min. The high filtration rate was rejected because of its proximity to the decibel value of 65 dB, which is known to increase the risk of heart and circulatory disease (Altura et al., 2018; Banerjee et al., 2014; Dzhambov and Dimitrova, 2016).

3.1. Droplet sizes

The particles measured directly at the outlet of the PARI Boy PARI LC SPRINT correspond to the aerosol sizes produced by aerosol formation. Of the aerosol particles produced, 81.5% were 0.5 μm or smaller (distance to outlet: 0 cm). Only 2.9% of the aerosols produced were 2.5 μm or larger. The total number of particles, directly at the outlet of the PARI LC SPRINT were 820,000 particles/L air. Up to a distance of 10 cm from the aerosol formation, the ratio between the particles sizes of 0.3 μm and 1 μm are stable. At a distance of >25 cm, the number of 1 μm sized particles decreases, whereas the percentage of 0.3 μm sized particles increases. The percentages of 1 μm to 2.5 μm particles increase to 25.5% and 19.8%, respectively, at a distance of 10 cm and decrease to values of <5% and < 1% at distances of ≥25 cm, respectively. The particles with a size of 0.5 μm decrease from 38.3% to 21.8%, whereas the percentage of the smallest particles measured (0.3 μm) increase to 73.2%. The total number of particles/aerosols was diluted to concentrations of 10^4 particles/L at distances of 25 cm and farther away from the PARI LC SPRINT.

3.2. Direct retention of viral aerosols by air filtration

The direct retention of phiX174-containing aerosols was examined by measuring the concentration of phiX174 phages at the outlet of the air purifier. This was done to distinguish between the retention of larger aerosol particles, when directly emitted into the air purifier. Distance and desiccation could not be found as being affecting factors. A reduction in viral aerosols was measured between 4.6 and 6.1 Log, which corresponds to a reduction of 99.9974–99.9999%.

3.3. Impact of distance on transmission

To determine the impact of distance on the transmission of viral aerosols, the emitting source (PARI Boy LC SPRINT) and the recipient (Coriolis μ) were positioned at 0.75 m and 1.5 m from each other. The initial number of detected phiX174 phages and the number of phiX174 phages collected at the respective distances were transferred into Log values.

The reduction rate was calculated as a mean value of three independent experiments; the error bars show the respective minimum and maximum value. Fig. 2 shows that at a distance of 0.75 m between the PARI Boy LC SPRINT and the Coriolis μ a reduction of 2.23 Log (mean) could be detected (1.67–2.57 Log). By increasing the distance of the 2 devices up to 1.5 m, a range of 2.53–3.64 Log reduction was measured (mean value of 2.97).

3.4. Air purification over time

To measure air purification using the described air purifier over time, the air was sampled directly after aerosol formation and after 5 min, which corresponds to 5–10 min after aerosol formation and then every 5 min up to a total time of 35–40 min after aerosol formation. Fig. 3 shows the results obtained in three individual experiments. Using the air purifier at a setting of 1000 m^3/h, the concentration of the phiX174 phages in the air were reduced by 2.86 Log. The experiments without the air purifier, nevertheless, showed a similar reduction rate of 2.61 Log after 35 min. Since the Coriolis μ operates as an air cleaner itself by suspension of the particles in the air for analysis (1.5 m^3), an additional experiment was conducted by using the air purifier and measuring the initial concentration in the air, as well as after 35 min of aerosol formation, to minimise the cleaning effect of the Coriolis μ to 3 m^3. The purifying effect of the tested air purifier without a minimal influence of the Coriolis μ was determined to be 1.12–1.67 Log within an operation time of 35 min.

3.5. Aerosol formation at the level of the suction opening

To determine whether the height of the suction opening and the resulting distribution of the virus-laden aerosols produced by the PARI LC SPRINT have a significant influence on the cleaning performance, the experiments on the factor time were repeated with variations in

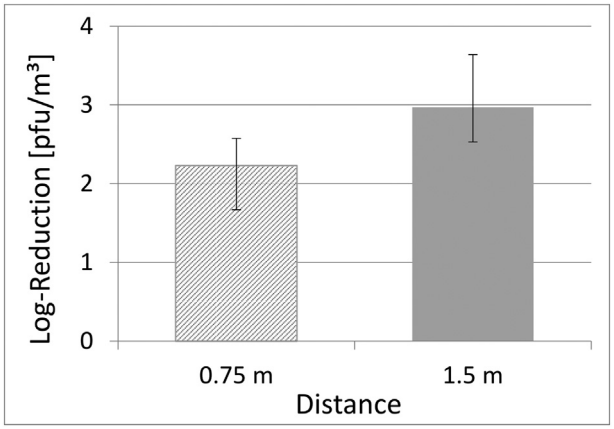

Fig. 2. Log reduction of phiX174 phage aerosols through distance.

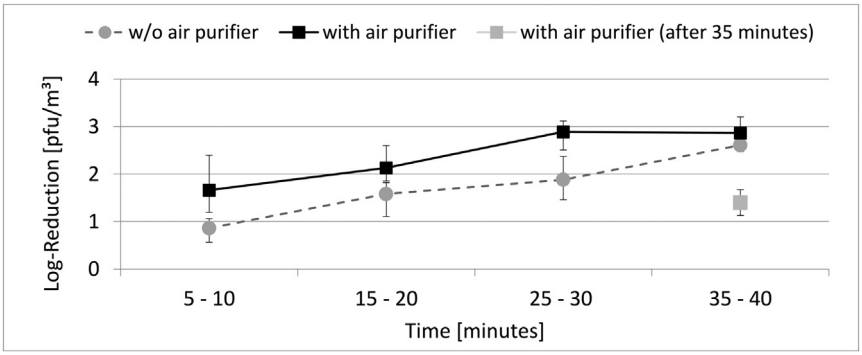

Fig. 3. Effect of the use of an air purifier on the concentration of phiX174 phages in aerosols. All experiments were conducted in triplicates. The points indicate the respective average, and the minimum and maximum values are shown by error bars.

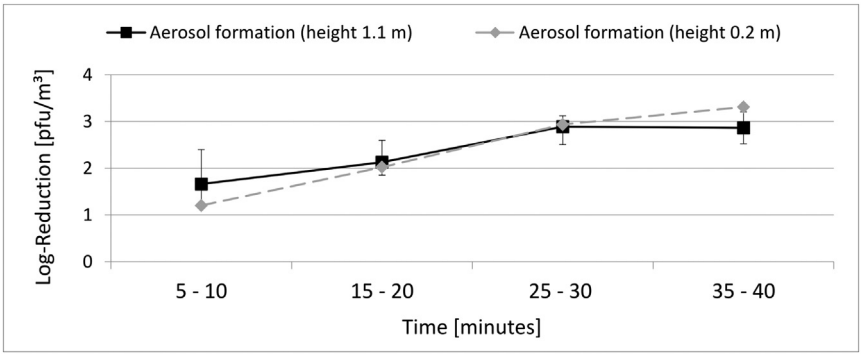

Fig. 4. Effect of the height at which aerosol formation was performed. The height of 1.1 m, was determined representative of a person sitting. The height 0.2 m was at the same level as the suction opening of the air purifier.

aerosol formation at the same height as the suction opening of the air purifier. Fig. 4 shows that the Log reduction was the same when the aerosol formation and the air suction were at the same height.

4. Discussion

The results of the presented study verifies the results of comparable work and the manufacturer promise in regard to the possible retention of viral aerosols through the applied air purifier. The concentration of phiX174 phages in aerosols was reduced by 99.9974–99.9999%, which meets the performance requirements of an H14 filter. Looking at the cleaning of the phiX174 phage using the air purifier in our experimental setup (Fig. 1), however, it was shown that the additional reduction using the air purification device was small.

The particles produced by the PARI LC SPRINT were generally smaller than 1 μm (Table 1). The proportion of very small particles (0.3 μm) at the outlet of the PARI LC SPRINT ranged from 43% to 57% of particles with a size of ≥0.5 μm. At a distance of 1.5 m, the ratio of very small particles increased to 73%.

When investigating potentially infectious aerosols, a distinction between the wet state and the dry state of the aerosol particles need to be made. Humidity has an influence on the individual size of the particles. Particles generated in the lungs or the respiratory tract are initially wet. Solids (such as salts, proteins, etc.) and viruses, which may be present, are included in these particles. If these wet aerosol particles leave the body, the aqueous phase evaporates within a short period of time if the humidity is moderate. It has been shown that an aerosol loaded with infectious viruses can lead to a COVID-19 infection as long as the liquid phase of the aerosol particles has not completely evaporated (van Doremalen et al., 2020; Pyankov et al., 2018). The evaporation time of aqueous aerosol particles with a diameter of a few micrometres is less than 1 s in moderate humidity (Cole and Cook, 1998). Ijaz et al. (1985) determined the survival of airborne human coronavirus 229E (HCV/229E) under different temperatures (20 ± 1 °C and 6 ± 1 °C) and relative humidity (RH) values. At 20 ± 1 °C, aerosolised HCV/229E was found to survive best at 50% RH, with a half-life of 67.33 ± 8.24 h. In ambient air, SARS-CoV-2 has a half-life of 1.1–1.2 h (Pyankov et al., 2018). The literature on the transmission of SARS-CoV-2 shows that particles <5 μm that contain the virus can remain airborne for at least 3 h (van Doremalen et al., 2020).

Studies have shown that 80% to 90% of the aerosols produced by speaking are approximately 1 μm in size and that aerosols that are <1 μm evaporate within seconds after emission (Borak, 2020; Cole and Cook, 1998). Lelieveld et al. (2020) postulated that the average aerosol produced in the respiratory tract is 5 μm, which shrinks upon exposure to particle sizes of <1 μm.

Whether aerosol particles containing SARS-CoV-2 are still infectious after evaporation of the liquid phase is currently under debate (Klompas

Table 1
Sizes of the produced aerosols measured with the PARI Boy LC SPRINT at different distances from the aerosol formation.

Distance (cm)	Percentage of particles (%)						Number of particles measured (particle/L)
	0.3 μm	0.5 μm	1 μm	2.5 μm	5 μm	10 μm	
150	73.2	21.8	4.3	0.5	0.1	0.1	10,673
100	76.5	19.0	4.0	0.4	0.1	0.1	12,019
75	71.8	24.0	3.8	0.4	0.1	0.1	8434
50	73.2	22.2	3.8	0.6	0.1	0.04	10,092
25	73.6	22.6	3.3	0.5	0.1	0.04	11,155
10	24.5	30.0	25.5	19.8	0.1	0.1	224,506
5	31.4	32.2	21.9	14.5	0.01	0.01	317,812
0	43.2	38.3	15.6	2.9	0.01	0.00	819,999

et al., 2020; Morawska and Cao, 2020). Another factor for the survival time of pathogens in aerosols is temperature. As temperature rises, virus survival time decreases (Tang, 2009). Low temperatures have been suggested to be ideal for airborne influenza virus survival, with survival time decreasing progressively at moderate and high temperatures (Lowen et al., 2007).

Distance is an infection control measure that has already been implemented and largely accepted by the public. Fig. 2 shows the effect of distance on the transmission from an emitting source to a recipient. Lelieveld et al. (2020) computed an algorithm to predict the possibility of infection by modifying different parameters. Using this algorithm, we calculated the number of aerosols produced by breathing, speaking, and singing for 5 min each. A period of 5 min was chosen to transfer the number of initial aerosol particles to the aerosol formation done in this study (Section 2.6). When looking at a super emitter, Lelieveld et al. (2020) also postulated that 30% of aerosols are laden with infectious viral particles. Using the algorithm of Lelieveld et al. (2020), it was found that 3000 aerosols are excreted by the average person in 5 min. Consequently, a super emitter expels 900 virus-laden aerosols in the same time frame. For speaking and singing, these numbers are multiplied by a factor of 10 each (30,000 aerosols per 5 min by speaking; 300,000 aerosols per 5 min by singing). Using these numbers for infectious aerosols on the data on reduction obtained in this study, it can be shown that distance alone has a substantial impact on a possible transmission (Fig. 5a). Individual cases can certainly turn out differently. The mean infection dose for transmission of SARS-CoV-2 has not yet been defined. The term "a few hundred" virus particles has been used (Beggs, 2020). Aerosol transmission by singing and at a distance of 1.5 m between 2 individuals poses a high risk of infection with a predicted concentration of 3.25 Log virus particles in 1 m^3 of air. Values are calculated by application of the algorithm computed by Lelieveld et al. (2020). The same transference was computed for the data concerning the reduction of viral aerosols by application of the air purifier in comparison to the reduction rate without the purification device (Fig. 5b).

Since the likelihood of a transmission in a room increases with the number of infected people inside a room and the length of stay, measures must be taken to limit the viral load in the air. However, it is currently not clear exactly how the SARS-CoV-2 concentration in the room should be measured and what reduction in concentration would be acceptable to limit the risk of transmission. Worldwide, many modern buildings have ventilation and air conditioning systems ensuring that

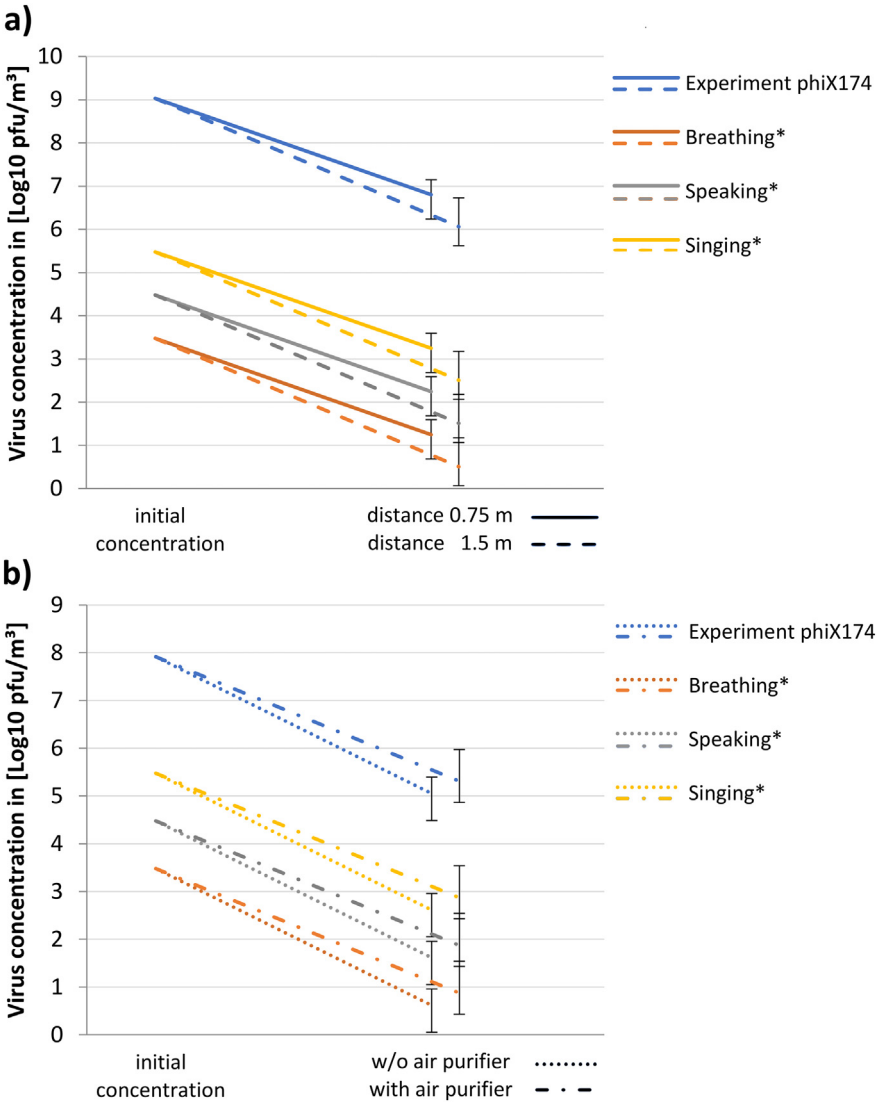

Fig. 5. Transfer of the results generated in the phage phiX174 experiments to average values for the emission of aerosols by breathing, speaking, and singing. a) Transfer of the reduction rate in regard to distance (0.75 m and 1.5 m). b) Transfer of the reduction rate in regard to the application of the air purifier.

the contaminated air is discharged and filtered or that fresh air is added from outside. In regions with moderate climatic conditions, however, natural ventilation by using windows and doors is used. Recommended air exchange rates are based on the CO_2 content in the air, the accumulation of pollutants in the room, and the prevention of building damage (e.g., mold formation). Ventilation is used to dilute and exchange the indoor air with fresh outdoor air and theoretically reduces the transmission risk. Air exchange rates by ventilation depend on wind direction and speed, the temperature difference, and the size of the window. The European norm EN 16798-3:2017 recommends supplying a certain amount of fresh air per hour, regardless of the CO_2 concentration, which can vary depending on the use of the room. In offices, restaurants, and sales rooms, the volume of the room should be exchanged up to 4 to 8 times per hour. If, however, pollutants that pose a significant health risk are emitted into the air in the room, such as viruses, significantly higher air exchange rates may be necessary (DIN 1946-4). For reducing the risk of infection with SARS-CoV-2, the German commission for indoor air hygiene recommends free ventilation a few times per hour for at least 3–5 min (Birmili et al., 2020). In addition to health aspects, comfort for the users of the room must also be considered. In winter, the coming winter months, or in colder climatic zones, it is important to note that long and frequent ventilation periods can lead to significant cooling of the room, which, besides discomfort, can also result in subsequent mold infestation.

The main advantage of the usage of ventilation devices compared to free ventilation is that they continuously guarantee adequate indoor air quality. In buildings without proper ventilation systems, the exchange of air by free ventilation is still the most adequate method for reducing the concentration of pathogens such as SARS-CoV-2. The above mentioned results, especially Figs. 3 and 5, question the added value of using an air purifier, which did show a significant reduction in virus concentration by direct filtration but did not show significant added effect in the described experimental setting. The experimental setup was chosen to reflect a real situation in a small, closed room without any additional air exchange besides that produced by the air purifier. Additional factors such as cleaning by the Coriolis μ could not be avoided but need to be taken into account when looking at the data. Studies with a similar research question differ from the experimental setup of the presented study in some critical points. Curtius et al. (2020) used air purifiers in a classroom setting and measured the concentration of particles in the air compared to a room with roughly the same size without the use of air purifiers. The researcher applied 3–4 air purifiers simultaneously in a room of about 180 m^3 with students and teachers present. Their data showed that using an air purifier had a positive effect on the concentrations of aerosols in the air. Another study used office environments (Küpper et al., 2019). Further experiments investigated the performance of air purifiers in a standardised test room with the help of reference particles and uniform distribution in the room (Kähler et al., 2020a). The respective authors stated that the position of the air purifier in the room is a critical factor. The results of the presented study verify the results of other studies and the manufacturer promise in regard to the possible retention of viral aerosols through the applied air purifier (see Section 3.2). An important factor to stress is the distribution of a cloud of viral aerosols produced by one infectious individual. An air purifier that is not directly in physical proximity of the emitting source cannot reduce the risk of transmission by direct exposition and may lead to a false sense of security. Air filtration as a tool for the reduction of pathogens in the air is a promising tool when used correctly and with great care (Kähler et al., 2020b; Exner et al., 2020). By applying a distance of 1.5 m between the emitting source, the recipient, and the air purifier with minimised additional air turbulence while the purifier is running, the additional reduction of viruses in aerosols could be less than 1 Log per m^3 of air. The application of air purifiers may reduce the risk of transmission by reducing the particle burden in the air (Curtius et al., 2020; Küpper et al., 2019; Kähler et al., 2020a, 2020b) but is not able to stop the direct transmission if the infected person (emitting source) is standing next to the susceptible person (recipient).

Maintaining distance has been shown to be an important risk-reducing factor for the transmission of viral aerosols. Various other studies have previously shown that particles in the air are limited in their movement through space, depending on a multitude of factors, such as turbulence, temperature, humidity, etc. (Gralton et al., 2011; Wells, 1934). The use of mobile air purifiers cannot replace other safety measures which have already been implemented, such as mouth and nose covers, masks and distance.

To the authors' knowledge, no other study has used viral aerosols for performance tests of mobile air purification so far. The use of phiX174 phages as a model for research on effects of measures on eukaryotic viruses is scientifically acknowledged. Using the culture-based method for detection proves that the aerosols contain vital virus particles after aerosol formation and sampling.

5. Conclusion

For testing the effectiveness of air purification devices with regard to the reduction of viruses, a test method involving test viruses has not existed until now. The use of bacteriophages (phiX174 phages) as presented here is a method to test the efficiency of air purification devices under experimental conditions. Using air purifiers with HEPA filters, a reduction of test viruses by 4.6–6.1 Log can be achieved when bacteriophages are applied directly in the air purifier, which corresponds to a reduction of 99.9974–99.9999%. By application of the air purifier in an experimental setup (experiment scenario 1, model 2), the reduction of phiX174 phages in the air could be additionally reduced up to 1 Log step (maximum value) by the air purifier in comparison to the experiments without the use of the air purifier (experiment scenario 1, model 1). The results presented need to be confirmed by further investigations. When applying mobile air purifiers, many factors, such as placement of the device in the room and additional air turbulence, need to be considered. The use of mobile air purifiers cannot replace other safety measures already in implementation, such as mouth and nose covers, distance, and ventilation. The results obtained using bacteriophages in aerosols, as presented in this study, should be confirmed by further investigations. The developed method could likely be used as a surrogate model to study the transmission risk via air of human pathogenic viruses in real life situations in the future.

CRediT authorship contribution statement

Nicole Zacharias: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft, Writing – review & editing, Supervision, Validation. **Alexandra Haag:** Conceptualization, Data curation, Investigation, Writing – original draft, Methodology. **Regina Brang-Lamprecht:** Data curation, Writing – original draft, Validation. **Jürgen Gebel:** Methodology, Writing – review & editing. **Sarah M. Essert:** Investigation, Writing – review & editing. **Thomas Kistemann:** Writing – review & editing. **Martin Exner:** Writing – review & editing. **Nico T. Mutters:** Writing – review & editing. **Steffen Engelhart:** Project administration, Writing – review & editing, Supervision.

Declaration of competing 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.

Acknowledgements

This study was not funded by additional parties. We would like to thank all colleagues who contributed to this work.

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Update

Science of the Total Environment

Volume 775, Issue , 25 June 2021, Page

DOI: https://doi.org/10.1016/j.scitotenv.2021.146775

Science of the Total Environment 775 (2021) 146775

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Corrigendum

Corrigendum to "Air filtration as a tool for the reduction of viral aerosols" [Sci. Total Environ. 772 (2021) 144956]

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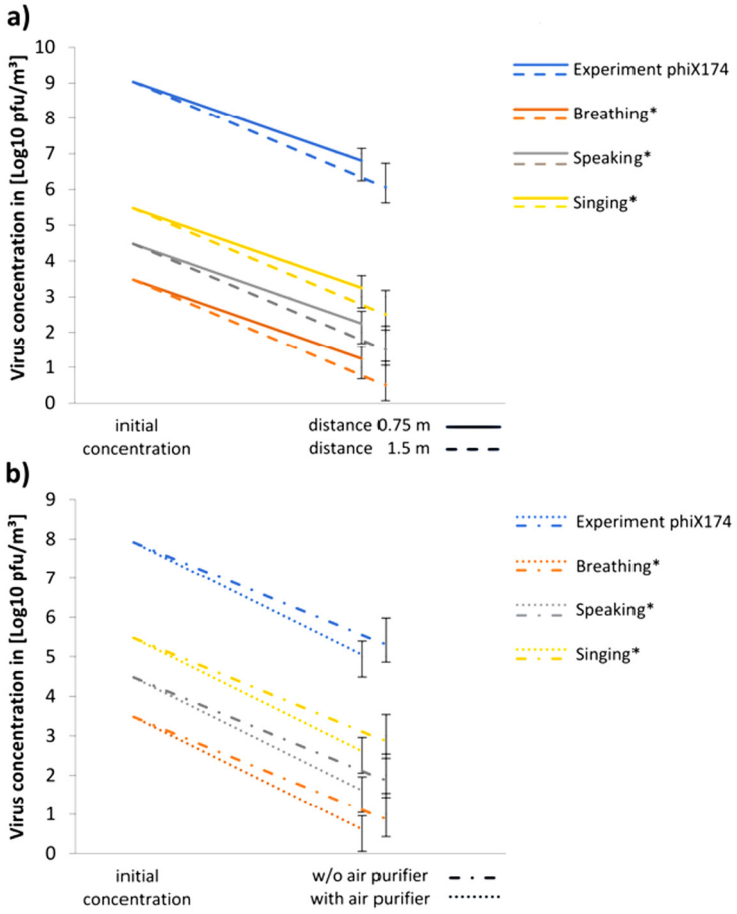
The assignments of the dashed lines "w/o air purifier" and "with air purifier" in Fig. 5b are not correct and must be read in reverse. A corrected version of the figure is attached. All statements in the text refer to the correct version and do not need to be changed. The authors would like to apologise for any inconvenience caused.



DOI of original article: https://doi.org/10.1016/j.scitotenv.2021.144956.
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https://doi.org/10.1016/j.scitotenv.2021.146775

Fig. 5 Transfer of the results generated in the phage phiX174 experiments to average values for the emission of aerosols by breathing, speaking, and singing. a) Transfer of the reduction rate in regard to distance (0.75 m and 1.5 m). b) Transfer of the reduction rate in regard to the application of the air purifier.

* Initial concentration of viral laden aerosol calculated using algorithm computed by Lelieveld et al. (2020).

Declaration of competing 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.