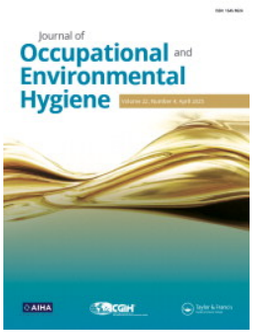

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REPORT

Use of portable air cleaners within an ambulance workspace

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ABSTRACT

Emergency medical service (EMS) providers face significant exposure to infectious aerosols during outbreaks like the COVID-19 pandemic. Most ambulances lack ventilation controls to reduce EMS worker exposure to these aerosols. Ambulances are smaller than hospital rooms and handle numerous patients daily, increasing contact with potentially infectious individuals. Ventilation controls such as portable high-efficiency particulate air (HEPA) filtration can mitigate this risk. Few studies have assessed portable HEPA filters in ambulances. This study evaluated two HEPA filter models in an unoccupied, stationary research ambulance at the National Institute for Occupational Safety and Health (NIOSH) in Cincinnati. A tracer aerosol simulated patient aerosol generation, and optical particle counters (OPCs) measured aerosols. The HEPA units were tested individually, placed in the same location, and operated for 50 min. Results showed significant reductions in aerosol concentrations during the generation phase, with performance varying during the decay period. Overall, HEPA units reduced particle concentrations by around 50% during the generation phase and continued to be effective through the decay period. This demonstrates the potential of portable HEPA filters as an affordable and effective option for air cleaning in ambulance patient modules.

KEYWORDS

Ambulance; bioaerosol; EMS, HEPA filtration; infection control, ventilation

Introduction

The importance of ventilation systems in reducing the transmission of infectious aerosols has been investigated over decades of research and brought to wider attention by the COVID-19 pandemic. Using portable air cleaners with high-efficiency particulate air (HEPA) filters has been a recommended ventilation control strategy for indoor settings. They can improve indoor air quality by removing 99.97% or more of particulates from the air they filter (Environmental Protection Agency 2021, 2023). These air cleaners can filter infectious aerosols to reduce exposure to bacteria and viruses, including SARS-CoV-2, the virus that causes COVID-19, influenza, and respiratory syncytial virus (RSV). These illnesses are transmitted when an infected person breathes out droplets and very small particles that contain the pathogen and a susceptible individual subsequently comes into contact with that pathogen, primarily through inhalation (Centers for Disease Control and Prevention 2021; Lee 2020; National Center for Immunization and Respiratory Diseases (NCIRD) 2022).

Emergency medical service (EMS) providers have the potential for significant exposure to infectious aerosols when treating emergency patients (Maudet et al. 2020). The traditional ambulance layout consists of the captain's seat (where OPC-1 is located), the CPR seat (where OPC-2 is located), and the bench seat (where OPC-3 and OPC-4 are located) (Kibira et al. 2013). EMS providers need to face and have within reach the patient; therefore, the closest locations are OPC-1, OPC-2, and OPC-3. These locations allow the providers to reach the patient's body and provide medical care during transport. OPC-2 is the seat for cardiopulmonary resuscitation which is not often used (Kibira et al. 2012).

They may perform aerosol-generating procedures such as endotracheal intubation that may generate infectious aerosols and droplets leading to increased risk of exposure (El-Boghdadly et al. 2020; Luo et al. 2020; Ng et al. 2020; Weissman et al. 2020). Although EMS providers use personal protective equipment to

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reduce exposure to SARS-CoV-2, further preventive measures need to be applied (Buick et al. 2020). Ambulances with air cleaning technology, such as built-in HEPA filters exist but are uncommon in practice and it can be relatively expensive for EMS providers to replace an ambulance or entire fleet of ambulances with newer models with these features (Horton Ambulances 2021; Wheeled Coach 2022; Ambulancemed 2023; RMA Group 2023). Many ambulances on the road have heating and cooling systems that simply recirculate the air and do not exchange it with outdoor air. Some manufacturers have started to install custom-made HEPA filtration on already constructed ambulances (Webasto Thermo & Comfort 2023). Nevertheless, more independent data are needed on the effectiveness and cost of different air cleaning technologies for ambulance patient modules.

For EMS providers that have not purchased a new ambulance with HEPA filtration or are waiting on a retrofit, another potential temporary option could be the implementation of portable HEPA air cleaners. Many studies have demonstrated the effectiveness of portable HEPA air cleaners in removing air contaminants (Cox et al. 2018; Bluyssen et al. 2021; Cadnum et al. 2023). More specifically, studies simulating SARS-CoV-2 virus exposure have been performed to evaluate air cleaning in different settings (Chen et al. 2010; Lindsley et al. 2021; Liu et al. 2022). Very few studies have evaluated ventilation controls in moving vehicles. A previous NIOSH study showed that a ventilation system inside an ambulance could reduce exposure to infectious aerosols (Lindsley et al. 2019). Air cleaners have also been studied in a school bus to reduce aerosol exposure in children (Lee et al. 2015). To our authors' knowledge, no additional research has been done on vehicular ventilation to control infectious aerosols. Therefore, there is a clear need to study the effects of ventilation controls in moving transportation vehicles, especially in ambulances, where exposure to infectious aerosols is likely to be higher than in similar healthcare treatment spaces within a building. Methods to evaluate the efficiency of HEPA filtration in these spaces include the use of mathematical modeling (e.g. computational fluid dynamics) (Chen et al. 2010) and nebulization of polystyrene particles measured with particle counters and aerodynamic particle sizers (Mead and Johnson 2004; Heo et al. 2021; Lindsley et al. 2021).

To further protect EMS personnel, the Centers for Disease Control and Prevention (CDC) has suggested opening the ambulance's doors after patient discharge at the hospital; thereby increasing air exchange and removing potential infectious aerosols inside the ambulance patient module (Centers for Disease Control and Prevention 2019, 2023). Portable HEPA filtration units could supplement the air exchange rate while in transit when it is not feasible to have the rear doors open and thus, could improve air quality and reduce worker exposure to infectious aerosols.

In the present article, we evaluated separately two different models of portable HEPA filtration units inside the patient module were evaluated separately. The portable HEPA filtration units had different characteristics such as clean air delivery rates (CADR) and induced airflow paths.

Materials and methods

Air filtration intervention

Portable HEPA filtration units

Two different portable HEPA filtration units were evaluated and can be observed in Figure 1. The first one was identified as HEPA-1 (Smart Purifier Bissell, Walker, MI) (Figure 1A and B, left); and the second one as HEPA-2 (GermGuardian, Guardian Technologies, Euclid, OH) (Figure 1A and B, right). The HEPA filtration units differed in a few ways: (1) manufacturer provided clean air delivery rates (CADRs) and measured face velocities across the outlet surface [HEPA-1 (172 CADR, 230-1350 feet per min) and HEPA-2 (99 CADR, 330-1100 feet per min)]; (2) HEPA filter sizes (Figure 1A); and (3) induced airflow direction. "Induced airflow" describes how air is drawn into and expelled from a HEPA filtration unit, and how this process alters the patterns of airflow in the surrounding environment. The induced airflow direction may impact the overall effectiveness of the unit if the airflow does not allow for proper room circulation. For example, HEPA-1's inlet was located in the front which included the whole front face, and the outlet was located at the top which resulted in air expelled upwards. HEPA-2's inlet was located on the back (had a smaller inlet size relative to HEPA-1) and the outlets were located on the left and right sides of the unit which resulted in air expelled from two sides (left and right) with smaller openings (Figure 1B). The filtered air expelled from the sides could get re-circulated due to the proximity to the inlet face, meaning air that has already been filtered would be filtered again instead of mixing with the ambient air, also referred to as "short-circuiting." Induced airflow can also cause inadvertent increases in the relatively small space of exposure in the

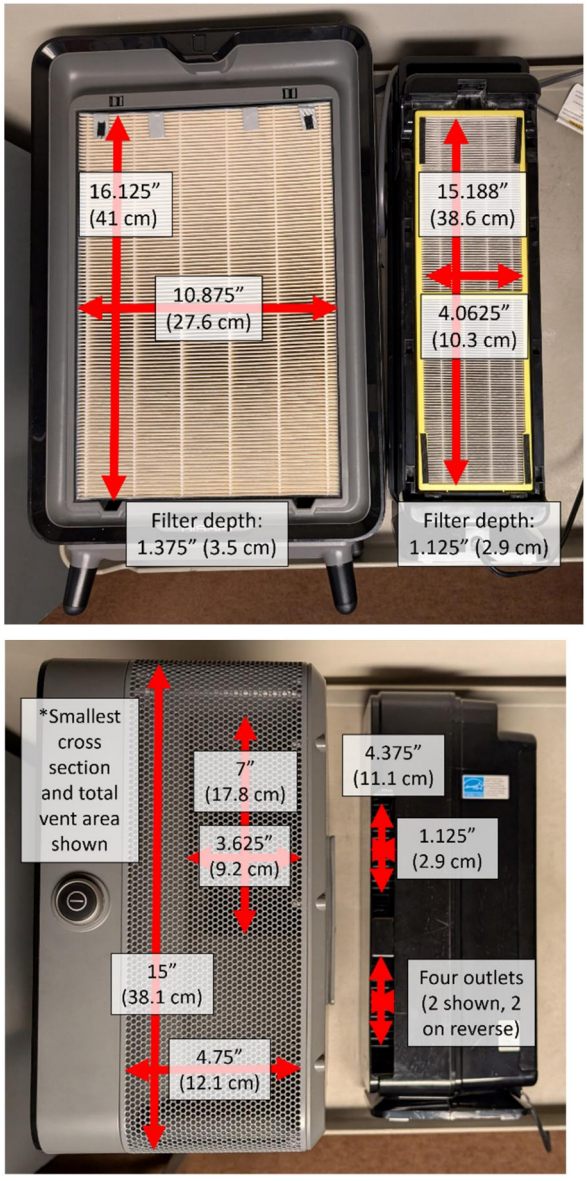

Figure 1. HEPA filtration intervention evaluated during the two sets of experiments: (A) HEPA-1 and HEPA-2 filter area dimensions and (HEPA-1 inlet is on the front of the device, HEPA-2 inlet is on the back of the device). (B) HEPA-1 and HEPA-2 outlet area dimensions (HEPA-1 outlet is on the top of the device, HEPA-2 has 4 outlets, 2 on both the left and right side [only 1 side shown]).

ambulance. Induced airflow may result in patient-generated bioaerosols being pulled or pushed through a worker's breathing zone.

Commercially available HEPA filtration units differ in a variety of ways including size and shape, and shape, inlet and outlet direction, and CADR. Given the small space and organizational needs of the ambulance cabin, the HEPA filtration units needed to fit in this space to prevent interference and must not interfere with the workflow of EMS providers or cause a trip hazard. Thus, the corner behind OPC-1 was the most preferable location to place the units; see Figure 2. This constraint considerably limits the number of available units that work available for use in the ambulance space. Two commercially available off-the-shelf HEPA filtration units were chosen from commercially available off-the-shelf options that fit within the confines of the space behind the rear-facing jump seat in the ambulance, as well as providing a range of CADRs. HEPA-1 was placed so the air inlet would be facing face the ambulance cabin behind OPC-1. The HEPA-2, to avoid creating a recirculation zone due to limited space, the unit was placed sideways in the corner behind OPC-1 to avoid creating a recirculation zone due to limited space (Figure 2).

Equipment and instrumentation

Nebulizers

The applied nebulization protocol was previously described in Pena et al. (2023). Two medical nebulizers (Model 85B 0000, PARI Innovative Manufacturing Inc., Midlothian, VA) and nebulizing cups were used to simulate a patient's aerosol generation. 1.6 to generate the droplet nuclei of 1.6 µm polystyrene latex (PSL) microspheres (4016 A Monosized Particles, Thermo Scientific) with a particle density of 1.05 g/cm^3 and size distribution of ±0.021 µm were used to generate the droplet nuclei. This particle size was selected as it is representative of infectious aerosols that can remain airborne for long periods, are readily inhaled, and are capable of deep lung deposition within the human respiratory tract (Mead and Johnson 2004).

Optical particle counters

To obtain particle concentration measurements, four OPCs were used (model 11-D GRIMM Aerosol Technik, Ainring, Germany). The instruments have 31 equidistant channels and can detect particles of sizes ranging from 0.253 to 35.15 μm, through light scattering. The OPCs were programmed to log data every 6 six seconds to provide an average particle concentration in particle number concentration (particles/L). Since the tracer aerosol had a particle size of 1.6 μm, the channel of interest was from 1.545 to 1.821 μm since the tracer aerosol had a particle size of 1.6 μm and only that size channel was analyzed for this study.

To measure particle concentrations at the breathing zone level of the EMS providers when inside the ambulance, NIOSH engineers developed four platforms of medium-density fiberboard and aluminum framing (80/20 Inc., Columbia City, IN). The

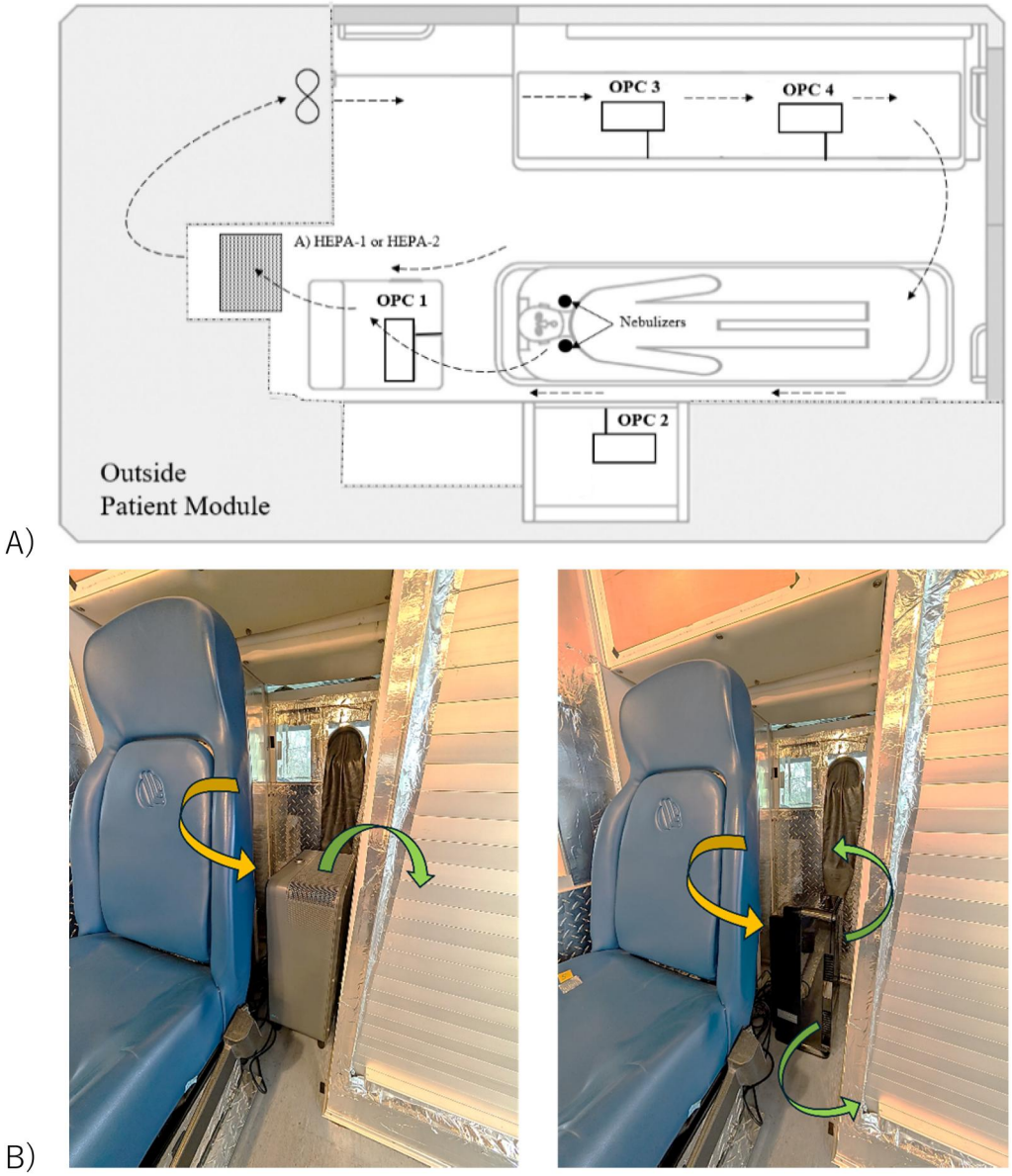

Figure 2. (A) Ambulance layout is shown. The portable HEPA filter systems (HEPA-1 or HEPA-2) are displayed. The ambulance HVAC system is represented as a fan in the upper left of the patient module and recirculates as well as tempers the air within the patient module. The dotted arrows show the airflow direction of the HVAC system, not the airflow direction of the HEPA filter units. A mannequin is also observed on the patient stretcher with two nebulizer cups as the source for aerosol generation. Four optical particle counters (OPC-1, OPC-2, OPC-3, OPC-4) were placed in four locations inside the ambulance for data acquisition. (B) HEPA filtration unit orientation. Yellow arrows indicate inlet air and green arrows indicate filtered air.

platforms were situated on four seats inside the ambulance and the OPCs were placed on top. The height of the platforms was determined with height measurements from the American Industrial Hygiene Association (AIHA) Engineering Reference Manual which has anthropometric data from the U.S. (Estill 1999). The data measurements initially considered were from the 95th percentile for women and the 50th percentile for men. Because the sitting eye height and sitting knee height were very similar for both male and female populations, the 95th percentile women's measurements were used. Finally, the sitting eye height (31″ in 78.74 cm) was added to the sitting knee height (21.5″ in 54.61 cm) minus 2″ in (5.08 cm) for the mouth level to obtain a final breathing zone height. Therefore, the final height of the platforms at which the OPCs were placed was 50.5″ in (128.27 cm) above the floor of the module.

Ambulance

A type III ambulance (Wheeled Coach, Winter Park, FL) was used to evaluate the effectiveness of the

portable HEPA units in reducing aerosol concentrations in the patient module. The ambulance was parked outside at the NIOSH facility located in Cincinnati, Ohio, and was connected to 120 V shoreline power during the experiments. Before all the experiments, openings in the patient module were sealed with aluminum foil tape including all, including exterior ports. This was to reduce the infiltration of environmental aerosols that could confound measurement results. Before each test, the ambulance engine was turned on to power the cooling compressor within the HVAC system, and the HVAC fan system was turned on and set to the highest airflow setting with the thermostat set to 75 °F. The HVAC fan was a recirculating system and pulls with no outdoor air used for heating and cooling. To simulate a patient inside the module, a mannequin was placed on the patient's stretcher. To control the nebulizer air pumps from outside the ambulance, the power cords were routed through a port located at the side of the ambulance patient module. The nebulizing cups were placed one on each side of the mannequin's face at the height of the mouth. The OPCs were placed on top of the platforms at each measurement location (shown in Figure 2) and turned on for particle sampling. Finally, the ambulance doors were closed, and the experiment was initiated.

For purposes of documenting environmental consistency, the temperature and relative humidity were collected with the HOBO H8 Pro Series loggers (MicroDAQ.com Ltd, Warner, NH) during each test to monitor the HVAC system. The temperature data were not used to assess the filtration systems but were used to troubleshoot any issues during the experimental set-up. The experiments were performed when outdoor temperatures were equal to or greater than 68°F (**20 °C**). Therefore, the ambulance HVAC system was in cooling mode when performing the tests throughout the entirety of each test.

Experimental setup

Figure 2A shows the ambulance layout with the location where portable HEPA filtration units were placed behind the rear-facing EMS provider seat. Exact airflow directions into HEPA-1 and HEPA-2 differ but both units pull air from the air directly surrounding them. The arrows in Figure 2A show the airflow direction of the HVAC system not the airflow direction of the HEPA filtration units. The arrows in Figure 2B illustrate the airflow direction of the HEPA filtration units in place from inlet air (in yellow) to filtered air (in green). The ambulance was stationary for safety reasons while performing all experiments with the HEPA filter units.

Experiments and data acquisition

Three experimental conditions were tested: (1) the baseline (without portable HEPA filtration units), (2) HEPA-1, and (3) HEPA-2. Once the experiment was finished, the OPC data were transferred and processed in a computer for the statistical analysis using SAS statistical software (Version 9.4, SAS Institute, Inc., Cary, NC).

The three conditions had 6 replicates each, making up a total of 18 tests. The completion order of the 18 tests was randomized by condition and 4–5 tests were performed per day in the order of this randomized list, and across multiple days to account for varying climatic conditions.

Baseline test condition

The general protocol consisted of three phases: (1) background particle removal, (2) aerosol generation, and (3) aerosol decay. During phase 1, the OPCs sampled background particle concentrations for 15 min without any HEPA filtration unit in place. In phase 2, the two nebulizers were turned on for 5 min for aerosol generation and then turned off. Finally, during phase 3 an aerosol decay was observed at three time intervals: 10, 20, and 30 min. Overall, a full experiment lasted 50 min.

Portable HEPA filtration units test condition

For the portable HEPA filtration unit test condition, the same protocol for the baseline case was followed with the addition of only one portable air cleaner, either HEPA-1 or HEPA-2, activated at the start of phase 1 and left on throughout the entire experiment. Each test condition for HEPA-1 and HEPA-2 was evaluated six times ($n = 6$).

Data analysis

Data processing

Particle count concentrations were measured during the background particle removal phase (phase 1) for each test. To establish a representative background concentration for analysis purposes, the last 3-min particle concentrations from phase 1 were averaged for each OPC on every replicate. This means four background OPC averages (OPC-1, OPC-2, OPC-3, and OPC-4) were obtained for every test. To account for the background concentrations in the data

analyses, the representative background concentration for each OPC during each test was subtracted from each data point collected by that OPC throughout the subsequent phases of the experiment. This was done for each replicate and each condition. Negative concentration values were generated when the measured data point was less than the average background. The negative numbers were retained to avoid skewing the data that could diminish the real effect of the HEPA filtration units; thereby, showing HEPA filtration units reducing aerosol concentrations lower than background levels. Finally, a cabin average concentration (determined after the correction of background concentration) was calculated from the average of the four OPCs for each experiment and condition.

The overall reduction percentages were calculated for the baseline, HEPA-1, and HEPA-2 conditions. The background corrected mean concentration during the aerosol generation phase of the baseline was used as the 100%-concentration since it was the control condition and had the highest peak concentration. To obtain the percentage reduction, the background-corrected mean concentration of each phase of each condition was subtracted from the background-corrected mean concentration of the baseline aerosol generation phase (phase 2) and divided by the background-corrected mean concentration of the baseline aerosol generation phase (phase 2). The equation used is shown below.

$$\text{Overall percentage reduction} = \left[\frac{\text{baseline AG mean} - \text{condition phase mean}}{(\text{baseline AG mean})}\right] \times 100\% \quad (1)$$

Statistical analysis

The statistical analyses were performed using SAS (Version 9.4, SAS Institute, Inc., Cary, NC), and one-way ANOVA with Tukey's Multiple Comparison tests were performed with a 95% CI and a level of significance of $p < 0.05$.

Sulfur hexafluoride test

A tracer gas test was performed to measure air leakage in the ambulance. One percent Sulfur hexafluoride (SF_6) was used as the tracer gas and a 1512 Photoacoustic Gas Monitor (Innova, LumaSense Technologies A/S, Ballerup, Denmark) sampled the SF_6 concentration in approximately 35 s intervals. SF_6 is a potent greenhouse gas with significant regulatory restrictions in California, Massachusetts (gas-insulated switchgear), New York (proposed), the European Union, and other jurisdictions due to its high global warming potential. The regulations primarily target reducing emissions from electric transmission and distribution systems. However, outside California and the EU, they do not cover the small fraction of SF6 used in research applications. SF_6 is a gas and as such would not be removed via mechanical filtration like a HEPA filter. Its use here is thus not as a test surrogate but only to measure outside air infiltration and provide context to particle measurements. For the experimental setup, the gas monitor was placed on the bench seat with one tube extension connected to four sampling ports with equally distant tube extensions to each location; each port was placed on the platform at each of the four locations. The ambulance engine was started, and the HVAC system was turned on at the highest flow setting. A portable axial fan was placed on the patient stretcher to facilitate air mixing and the doors were closed. Many standards and guidelines for tracer gas decay testing, such as those from ISO or ASTM, recommend or require the use of mixing fans to achieve uniform tracer gas distribution during the measurement process. Mixing fans help reduce measurement errors caused by localized air movement, such as drafts or temperature-driven convection currents, which could lead to an uneven distribution of SF_6. A NIOSH engineer stayed inside the ambulance holding a gas sample bag filled with the 1% SF_6 tracer gas. The gas monitor was turned on and once it started sampling, the engineer opened the valve and squeezed the bag for approximately 7 sec, exited the ambulance with the SF_6 bag, and closed the doors. The engineer waited 30 sec to allow for the mixing of air in the ambulance before recording the data for the start time of the concentration decay curve. Then, the highest SF_6 concentration peak was recorded, and the concentration was monitored from outside the ambulance until the peak concentration was reduced by 99%. Six replicates ($n = 6$) of data were collected.

Results

The data presented in Figure 3 are background-corrected 5-point moving averages from the three test conditions (Baseline, HEPA-1, and HEPA-2) in particles/L versus time during all experimental phases.

The results reported here represent the average of the concentrations of the four locations (OPC-1, OPC-2, OPC-3, and OPC-4) inside the patient module

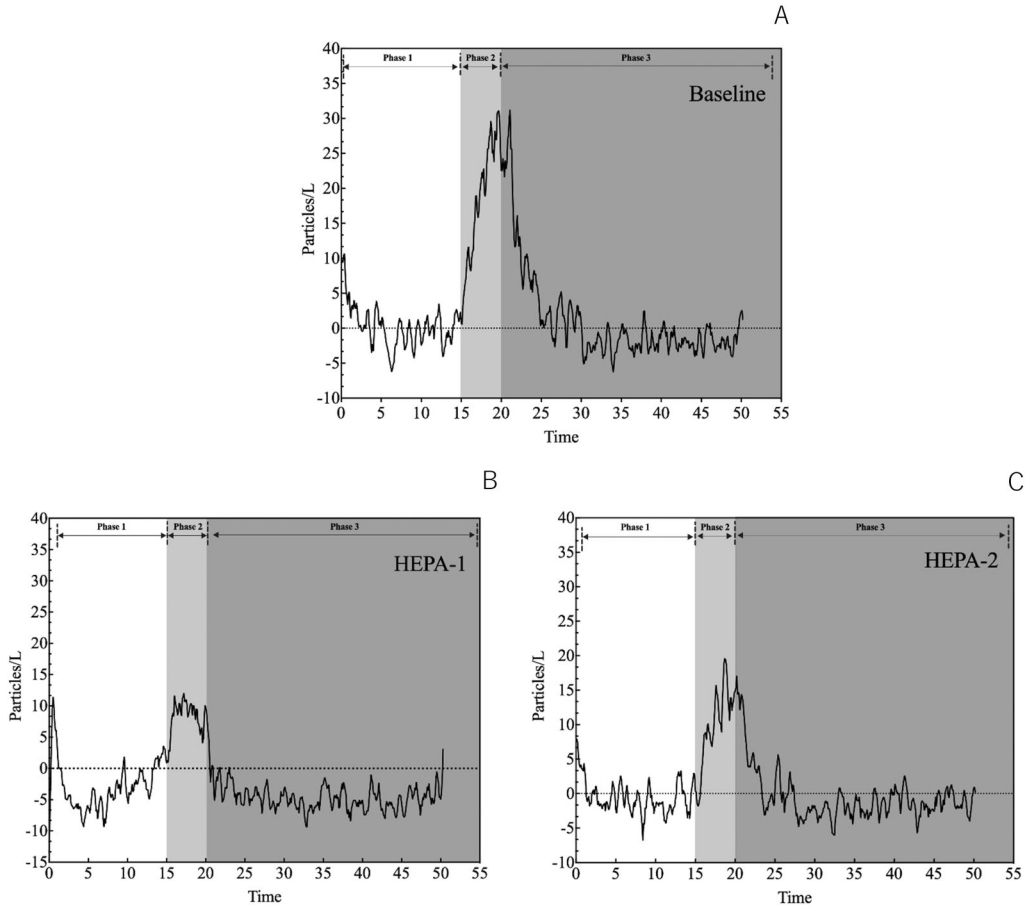

Figure 3. The 5-point moving average of the raw data from the three experiments is shown in particles/L *vs*. time. (A) baseline, (B) HEPA-1, and (C) HEPA-2. The different phases can be observed: phase 1 (background particle removal), phase 2 (aerosol generation), and phase 3 (decay); ($n = 6$).

and the six replicates of each condition. Particle concentrations in particles/L in this results section are background-corrected values. Thus, a value of 00 particle/L means that the particle concentration was equal to the measured average concentration minus the background average concentration.

Overall, current results showed that HEPA-1 and HEPA-2 reduced peak aerosol concentration by 46–55% during a 5 min simulated aerosol-generating procedure compared to without the presence of a portable HEPA filtration unit. The HEPA-1 and HEPA-2 continued to reduce the aerosol concentration over the following 30 min to below the background level.

Baseline

For the baseline case, a peak concentration of around 30 particles/L was observed during aerosol generation (phase 2) right before minute 20 (Figure 3A). After the first 5 min of phase 3, the aerosol concentration went down to <5 particles/L, but the concentration continued to somewhat oscillate until the end of the phase.

HEPA-1 and HEPA-2

Lower concentration peaks during aerosol generation (phase 2) can be observed for both HEPA-1 (<15 particle/L; Figure 3B) and HEPA-2 (<20 particles/L; Figure 3C) than for the Baseline condition (∼30 particles/L; Figure 3A). At the start of phase 3, HEPA-1 reached a concentration of around zero and continued to lower particle concentrations. HEPA-2 reached a concentration of <5 particles/L during the first 5 min of phase 3 and had a fluctuating decay with concentrations near zero for the rest of the phase.

Average particle concentration of baseline, HEPA-1, and HEPA-2 conditions

Figure 4 shows the average concentrations in particles/L of the three conditions (baseline, HEPA-1, and HEPA-2) during the three phases of the

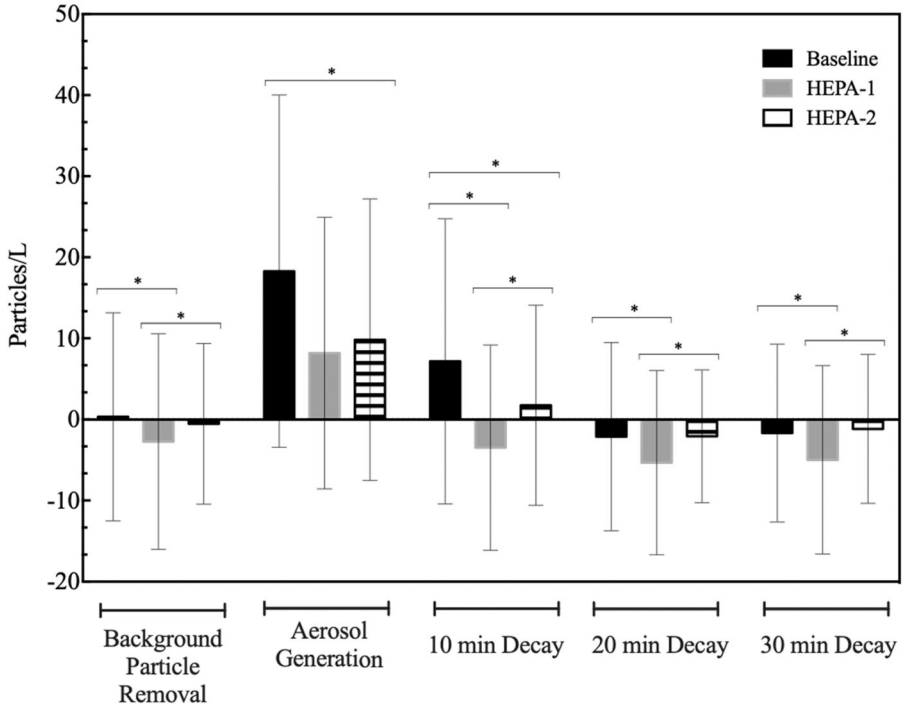

Figure 4. Average particle concentrations in particles/L are shown during the aerosol generation and decay phases for the baseline, HEPA-1, and HEPA-2. One-way ANOVA was performed. Statistical differences are shown with an asterisk ($p < 0.001$); ($n = 6$). Error bars represent the standard deviation.

experiment: background particle removal (phase 1), aerosol generation (phase 2), and decay (phase 3) at 10, 20, and 30 min. The background particle removal phase is included to observe the initial average particle concentrations before the aerosol generation phase. The baseline case, during aerosol generation, showed an average concentration of ~18 particles/L. In the first 10 min, it reduced the concentration to ~7 particles/L, and after 20 min below the background concentration.

During the aerosol generation phase, the HEPA-1 and HEPA-2 cases showed a reduction in particle concentrations to less than 10 particles/L. At 10 min, HEPA-1 reached a concentration below the background concentration and kept reducing the concentration throughout the rest of the decay phase. HEPA-2, on the other hand, reached a concentration of less than 5 particles/L after 10 min, and below background after 20 min.

There were statistical differences ($p < 0.01$) among conditions at all phases. During the background particle removal phase, the baseline case was statistically different than HEPA-1 but not from HEPA-2 (baseline condition having more particles/L, see Figure 4), while the performance of the HEPA filtration units was statistically different from each other (HEPA-2 condition having more particles/L, see Figure 4). Additionally, during aerosol generation, the particle concentration during the baseline case was statistically higher than HEPA-1 and HEPA-2, but there was no statistical difference among the HEPA filtration units. The concentrations from the HEPA-1 test condition were statistically lower than the baseline case at 10, 20, and 30 min (one-way ANOVA, $p < 0.01$). The concentrations from the HEPA-2 test condition were statistically lower than the baseline case only at 10 min (one-way ANOVA, $p < 0.01$). Particle concentrations from the HEPA-1 condition were lower than the HEPA-2 condition at all decay times (10, 20, and 30 min). Therefore, the overall performance of HEPA-1 was found to be superior to HEPA-2. This is expected as HEPA-1 has a higher CADR number, filter size, and air intake dimensions. Figure 4 shows average particle concentrations and statistical differences for all conditions and phases.

Overall percentage reduction of particle concentration

The percentages of reduction of the baseline case, HEPA-1 and HEPA-2 were calculated and are shown in Table 1. The concentration used to calculate the percentages of reduction was the mean concentration of aerosol generation of the baseline case (18.3 particles/L). This phase was considered the experimental control since it did not use any HEPA filtration unit

Table 1. Mean particle concentrations (particle/L) and overall percentages of particle reduction for each condition during each phase.

Condition	Baseline	HEPA-1	HEPA-2
Aerosol generation	18.28	8.18	9.83
	0%	55.2%	46.2%
10 min decay	7.17	−3.46	1.74
	60.7%	>100%	90.4%
20 min decay	−2.12	−5.32	−2.08
	>100%	>100%	>100%
30 min decay	−1.68	−1.16	4.98
	>100%	>100%	>100%

intervention. For that reason, the reduction percentage reported in Table 1 for that phase and test condition (baseline aerosol generation phase) is zero.

After 10 min, the baseline case had an overall reduction of particle concentration of approximately 61%, and after 20 min, greater than 100% (Table 1).

HEPA-1 had a reduction of approximately 55% during aerosol generation, and over 100% after 10 min, continuing to reduce the concentrations throughout the end of the decay phase. On a similar note, HEPA-2 had a reduction of approximately 46% during the aerosol generation phase, a reduction of 90% after 10 min, and a reduction of greater than 100% after 20 min.

Sulfur hexafluoride (SF_6) concentration

The collected tracer gas decay curve was used to estimate an air change rate for the patient module. The line of best fit was added over the plot of the natural log of SF_6 concentration *vs.* time in hours (hr) for the subset of the curve starting at the peak of the concentration and ending at 1% of the peak concentration. The slope of this calculated line of best fit was used as the estimated air change rate in air changes per hour (ACH). The graphs of all six replicates and their calculated line of best fit are shown in Figure 5. An average ACH of 6 was measured.

Discussion

The present study aimed to evaluate a HEPA filtration intervention to reduce aerosol concentrations inside the ambulance patient module. Two portable HEPA filtration units were placed one at a time inside the patient module. To simulate a real-life exposure scenario for EMS personnel, droplet nuclei were generated as a tracer aerosol originating from two medical nebulizers positioned near the mouth of a patient mannequin. Aerosol "exposure" concentrations were measured using four OPCs strategically placed at the breathing zone levels of EMS seat locations within the

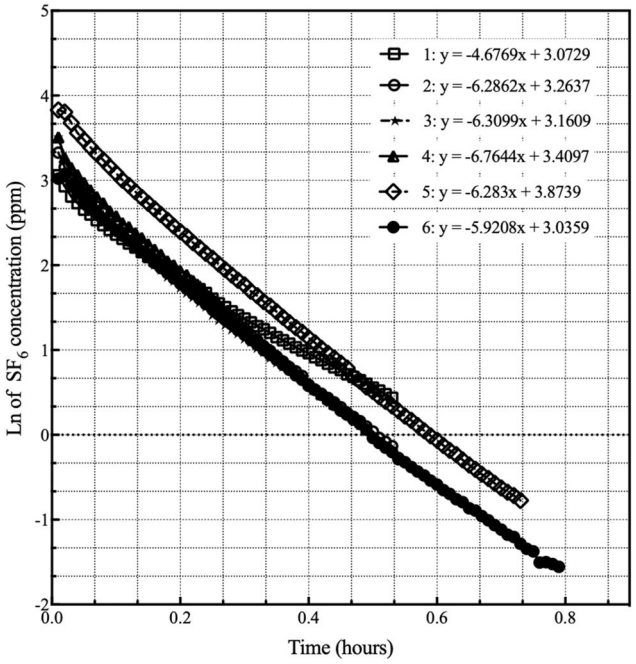

Figure 5. Concentration of the SF_6 in parts per million (ppm) over time in hours. 1 to 6 legends indicate trial number ($n = 6$).

patient module. To obtain further information regarding airflow behavior, tracer gas tests using SF_6 were performed to obtain air change rates inside the patient module.

Portable HEPA filtration units

The two portable HEPA filtration units evaluated in this study were from different manufacturers and varied in CADR and induced airflow parameters. Therefore, several factors resulted in observed differences in particle concentrations inside the ambulance patient module using the portable HEPA units. For example, HEPA-1 has a higher CADR of 172 cfm (smoke), while HEPA-2 has a CADR of 99 cfm (smoke). The CADR standardized measurement system is used to rate the performance of air cleaners (Environmental Protection Agency 2021). Participating manufacturers certify their air purifiers through the Association of Home Appliance Manufacturers (AHAM) which evaluates the performance of the unit for removing air pollutants such as tobacco smoke, dust, and pollen following a specified test protocol (Association of Home Appliance Manufacturers 2021). The AHAM certification includes three CADR numbers (tobacco smoke, dust, and pollen) for each air cleaner. The CADR number provides the volume of effectively filtered air delivered by the air cleaner. The higher the number, the faster it removes the contaminant. The CADR number of interest for this study was the tobacco

smoke that has a particle size from around 0.1 µm to 1 µm (Keith and Derrick 1960).

This space within the patient module was limited with walls on three sides. Therefore, the location and orientation could influence filtration performance. Further experiments or modeling of portable HEPA filtration units in different locations or orientations inside the patient module could provide additional information on how location could impact the performance of the HEPA filtration unit in an ambulance and the ability to effectively reduce worker exposures.

Experimental protocol

Aerosol-generating procedures such as intubation are often not recommended in prehospital environments (Gnugnoli and Shafer 2023). One of the challenges behind this recommendation is the level of expertise required to perform intubation, for example between non-physician and physician providers. Complications during airway interventions may emerge and result in failed patient intubation (Lockey et al. 2015). Moreover, prehospital intubation can have other complications such as hypoxia, hypotension, tracheal tube misplacement, esophageal intubation, vomiting and aspiration, cardiac arrhythmia, bleeding, and dental damage (Crewdson et al. 2017). Nevertheless, there are situations when the EMS provider may perform airway interventions such as during cardiac arrest or as otherwise determined by the EMS provider (Crewdson et al. 2018). We evaluated the generation of infectious aerosols in spike concentrations instead of constant concentration to simulate the intubation or another aerosol-generating procedure. Typically, patient intubation should take around 30 s (Lane et al. 2004). However, it was important to evaluate the transient behavior immediately following the spike concentration using the filtration units, thus the analysis covered 30 min after intubation to capture the longer-term effect of an aerosol-generating procedure. However, if a HEPA filter unit is installed inside the ambulance cabin, it should be always running during patient transport, especially during the respiratory virus season, not just during aerosol-generating procedures.

The protocol for the aerosol generation phase was generally the same for the baseline case, HEPA-1, and HEPA-2 with the addition of the portable HEPA filtration units which were turned on during the corresponding conditions. It was expected that both HEPA conditions would have significant reductions in particle concentration during the aerosol generation phase (phase 2). The baseline case demonstrated the natural decay curve, while the inclusion of HEPA filtration units demonstrated the performance of an intervention to reduce aerosol concentrations within the patient module. The HEPA-1 and HEPA-2 conditions performed better than the baseline case, and HEPA-1 exhibited better performance among the two HEPA filtration units. This was expected as HEPA-1 had a larger CADR, delivering 72% more clean air than HEPA-2.

The standard deviation was very high in the statistical analysis. It is possible that the 5-min duration of the aerosol generation phase (phase 2) might not be enough to provide a homogenous aerosol distribution among the four OPCs inside the module. This may have contributed to the high standard deviation between OPCs. The smaller sampling time of 6 s may be another cause. However, increasing the time of the aerosol generation phase (phase 2) would not be realistic because the experimental protocol aims to mimic aerosol-generating procedures, such as the intubation process that may take a few seconds to a minute to perform. Moreover, these differences in aerosol concentrations inside the patient module also reflect differences in exposure among locations within the patient module which is not in a perfectly-mixed space under steady state.

Another important aspect to consider is the assessment of background concentration. Background concentrations were obtained during the background particle removal phase (phase 1), and the last 3 min were averaged as the background concentration level to be removed. This background correction enabled the experiment to better focus on the concentration build-up and decay of the tracer aerosols generated within the patient module. The background concentrations were averaged and subtracted from the original raw data. This resulted in negative numbers in some cases as the presence of the HEPA filtration units cleaned the air, beyond what was occurring in the natural environment to below background.

Finally, temperature is another factor that may affect airflow patterns. As mentioned before, the ambulance used in this study had a heating and cooling system. The air was recirculated and there was no outside air intake. To minimize changes in air patterns, the heating was turned on during the cold season, and the cooling system was turned on during the hot season. This way, temperature differences were incorporated into the average aerosol reduction in a real-world way. The heating and cooling system always operated on the highest airflow setting, and given the recirculating nature of the system, it should

not have contributed meaningfully to the particle reduction. However, changing the fan setting could change pressure imbalances and thus air infiltration rates. Leaving the system set to high eliminated this variable.

Findings

The performance of the HEPA filtration units was evaluated during two distinct experimental stages, the aerosol generation phase, and the decay phase. During the aerosol generation phase, which mimicked a concentration buildup such as during an aerosol-generating procedure, the HEPA test conditions revealed protective exposure reductions exceeding 55% (HEPA-1) and 46% (HEPA-2). Data analyses over three time periods of decay (10, 20, and 30 min) were conducted to assess the HEPA filtration units 'ability to dilute a contaminant concentration once it was generated. At 20 and 30 min, all three conditions were below the background. By examining the concentrations at 10 and 20 min, it was observed that HEPA filtration units reduced aerosol concentrations below background concentration much faster than the baseline case. This was especially evident in the first 10 min following the aerosol generation phase, thus reducing both the short-term peak aerosol exposure as well as the total exposure over the 30-min test period.

Air infiltration

A tracer gas test with sulfur hexafluoride (SF_6) was performed to check for any leaks in the patient module that might dilute the inside aerosol concentration. The patient module and driver module did not share an HVAC system and the air movement between the driver and patient module was reduced as much as reasonable. An average of 6 air changes per hour (ACH) was observed, which is high for a sealed vehicle. Therefore, the baseline case had a fast natural decay despite sealing the ambulance at all ports and cracks between the driver's compartment and the patient module. Both the aerosol and tracer gas tests indicated appreciable air leakage into the ambulance patient module that could not be fully mitigated. The high air exchange rate measured in the ambulance module during the tracer gas decay test was likely to be attributed to two primary factors. First, the ambulance module was not completely airtight, allowing for some air leakage even with the doors closed and sealing efforts in place. Second, the HVAC system within the module likely generated airflow and pressure imbalances, which could have exacerbated the air leakage. In the small internal air volume of the ambulance module, even minor air leakage can contribute to a substantially higher air exchange rate compared to what would occur from similar leakage in larger volume spaces. The research vehicle in which the tests were conducted was over 15 years old and leaks within the HVAC system pathway are suspected but could not be confirmed. In the absence of such leaks, the protective impact of particle reductions associated with the HEPA interventions would likely be greater. In a real-world scenario, an ambulance would also have air movement from and to the exterior, perhaps even greater than was found in this research vehicle. This would serve to further dilute any infectious aerosols inside the cabin. Thus, current results may be conservative while real-world aerosol decay may occur faster. Future research could validate this assertion.

Although portable HEPA filtration units have not yet been broadly implemented in ambulances, there are a few examples of real-life applications. One study evaluated a high-efficiency cabin air (HECA) system installed inside a school bus and found that it effectively reduced the exposure to vehicle pollutants among children. Other groups are studying containment and filtration systems for potential use in ambulances (Cranfield University 2021; Lyng 2021; Klein Leichman 2022). However, to the authors' knowledge, more studies with concrete data have not been published.

Further research could include (a) evaluating different HEPA unit orientations, inlet/outlet modifications, and locations inside the ambulance to determine filtration performance, (b) performing the experiments in a more controlled indoor environment removing all background concentrations, and (c) evaluating the portable HEPA units with culturable infectious aerosols instead of a tracer aerosol surrogate. Additional tests should be performed to ensure that the HEPA filtration units are safely secured when used with the vehicle moving, as is required for all equipment in the cabin. The vehicle moving at speed may induce air pressure gradients around the outside of the cabin that will affect air infiltration rates and thus particle clearance times. There will also be other inertial air effects from vehicle motion that would be less likely to impact ventilation effectiveness but could change air distribution patterns and worker breathing zone concentrations. Future research should help to quantify the effect of these variables.

Limitations

While the findings show a possible intervention to reduce worker exposure to bioaerosols, there were

limitations to this study. These included: (1) stationary operation of the vehicle, (2) modified ambulance inlet and outlets, (3) use of a monodispersed non-biological aerosol surrogate, (4) testing of two HEPA filtration units that were unsecured. Further research could address and quantify these limitations by: (a) evaluating different HEPA unit orientations, inlet/outlet modifications, and locations inside the ambulance to determine filtration performance, (b) performing the experiments in a more controlled indoor environment removing all background concentrations while minimizing changes to ambulance air inlets/outlets, (c) evaluating the portable HEPA units with culturable infectious aerosols instead of a tracer aerosol surrogate, and (d) ensuring that the HEPA filtrations units are safely secured when using with the vehicle moving, as is required for all equipment in the cabin. The vehicle moving at speed may induce air pressure gradients around the outside of the cabin that will affect air infiltration rates and thus particle clearance times. There will also be other inertial air effects from vehicle motion that would be less likely to impact ventilation effectiveness but could change air distribution patterns and worker breathing zone concentrations.

Conclusions

Overall, this study showed that the use of HEPA filter units helped reduce aerosol concentrations inside the patient module of an ambulance, both during the aerosol generation phase and during the post-generation decay phase. Air flow direction, HEPA filter unit sizes, and CADR ratings are all characteristics that may be considered when choosing an air cleaner as well as the location to be safely placed inside the patient module. Even though the performance of the evaluated HEPA units varied, the HEPA units significantly reduced particle concentrations during aerosol generation by around 50% and continued to do so until the end of the decay period. Although some ambulance manufacturers offer HEPA filtration systems integrated into the design of new ambulances, their adoption has not been widespread, possibly due to the loss of airflow resulting from the HEPA filter's large pressure drop. At least one company offers a HEPA retrofit kit for existing ambulance patient modules. As awareness increases of the role ventilation plays in reducing infectious aerosols, this may become a more requested option, but it takes time to replace the nation's ambulance fleet with HEPA-filtered patient modules. Portable HEPA air cleaners could be a temporary option to reduce the exposures of EMS providers inside the patient module, especially during a pandemic response.

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Author contributions

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Data availability statement

The data that support the findings of this study are available from the corresponding author, reasonable request.

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