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Use of a Negative Pressure Containment Pod Within Ambulance-Workspace During Pandemic Response

*Emergency medical service (EMS) providers have a higher potential exposure to infectious agents than the general public (Nguyen et al., 2020, "Risk of COVID-19 Among Frontline Healthcare Workers and the General Community: A Prospective Cohort Study," Lancet Pub. Health, **5**(9), pp. e475–e483; Brown et al., 2021, "Risk for Acquiring Coronavirus Disease Illness Among Emergency Medical Service Personnel Exposed to Aerosol-Generating Procedures," Emer. Infect. Disease J., **27**(9), p. 2340). The use of protective equipment may reduce, but does not eliminate their risk of becoming infected as a result of these exposures. Prehospital environments have a high risk of disease transmission exposing EMS providers to bioaerosols and droplets from infectious patients. Field intubation procedures may be performed causing the generation of bioaerosols, thereby increasing the exposure of EMS workers to pathogens. Additionally, ambulances have a reduced volume compared to a hospital treatment space, often without an air filtration system, and no control mechanism to reduce exposure. This study evaluated a containment plus filtration intervention for reducing aerosol concentrations in the patient module of an ambulance. Aerosol concentration measurements were taken in an unoccupied research ambulance at National Institute for Occupational Safety and Health (NIOSH) Cincinnati using a tracer aerosol and optical particle counters (OPCs). The evaluated filtration intervention was a containment pod with a high efficiency particulate air (HEPA)-filtered extraction system that was developed and tested based on its ability to contain, capture, and remove aerosols during the intubation procedure. Three conditions were tested (1) baseline (without intervention), (2) containment pod with HEPA-1, and (3) containment pod with HEPA-2. The containment pod with HEPA-filtered extraction intervention provided containment of 95% of the total generated particle concentration during aerosol generation relative to the baseline condition, followed by rapid air cleaning within the containment pod. This intervention can help reduce aerosol concentrations within ambulance patient modules while performing aerosol-generating procedures.* [DOI: 10.1115/1.4056694]

Introduction

The high demand for emergency medical service (EMS) providers during the COVID-19 pandemic has highlighted the importance of their occupational safety and health. EMS workers have a higher potential for exposures to infectious agents than the general public [1,2]. This is in part because ambulances are around one-third to one-sixth of the volume of a normal patient room and typically have minimal heating, ventilation, and air conditioning (HVAC) systems [3,4]. Furthermore, EMS workers may perform procedures such as field intubation on a patient causing bioaerosol generation in the confined space of the ambulance [5]. Severe cases of COVID-19 may require aerosol-generating procedures, including intubation and mechanical ventilation, exposing the healthcare workers to patient generated bioaerosols and droplets [6,7]. Several studies at the beginning of the COVID-19 pandemic reported exposure of healthcare workers to bioaerosols when intubating a COVID-19 patient in hospital settings [6,8–11]. A recent study highlighted that 16% of COVID-19 patients required procedures that caused bioaerosol generation. Although only 1% of the EMS calls over the study period were COVID-19 related, more

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(*a*) (*b*)

Fig. 1 Containment and filtration intervention evaluated during the two sets of experiments: the containment pod with HEPA-filtered extraction systems (*a*) CP-HEPA-1 and (*b*) CP-HEPA-2

than half of the EMS workforce was transporting COVID-19 patients and therefore had potential exposure, imposing a major risk to first responders [2].

Several guidelines have been published by the Centers for Disease Control and Prevention (CDC) and the Occupational Safety and Health Administration emphasizing the protection of healthcare workers. Some recommendations for ambulance cleanup include (a) disinfecting with Environmental Protection Agency-registered products (list N) and (b) the opening doors of the stationary ambulance to enhance natural ventilation [12–15].

Furthermore, it has been reported by the CDC that the time for patient exchange and documentation while at the hospital, with the rear ambulance door open, provides enough time for the air inside the patient module to be replaced and for the removal of infectious particles [12]. Nevertheless, worker protection remains a priority and additional preventive controls could reduce worker exposures even further during the current and potential future pandemics.

Patient-generated bioaerosols may deposit in the respiratory tract, which includes the extrathoracic, bronchial, and alveolar airways. The extrathoracic airway includes the nostrils, nasal cavity, pharynx, and larynx. Particles of around 10 μm and larger may deposit in this region. The bronchial airway includes the trachea, the branching to the bronchi, and the bronchioles. Particles of around 2.5 μm can reach this region and may deposit there as well. Finally, the alveolar airway includes the alveoli, and the particle size for particle deposition in this region is around 0.1 μm [16–18]. The SARS-CoV-2 virus may deposit in the bronchial and alveolar airways, which can lead to respiratory airway infection [19].

To reduce exposure to bioaerosols inside an ambulance, further preventive measures can be applied. Several groups have developed containment barriers such as transparent boxes and drapes, enclosing the patient's head (aerosol source), since the beginning of the COVID-19 pandemic to reduce bioaerosol exposure from bioaerosol-generating procedures [20–25]. In May 2020, the U.S. Food and Drug Administration (FDA) provided an emergency use authorization for developing passive protective containment barriers [26]. However, further research suggested that these barriers were concentrating aerosols and, thereby, potentially increasing the risk of infection to workers [27–30]. Thus, the FDA recommended the use of the barriers only in combination with negative pressure [26]. Ambulances with whole body negative pressure and isolation stretchers have proven effective at reducing the risk of exposure but are not broadly available [31,32]. Except for some isolation units (e.g., for Ebola) [33], such portable and permanent containment barriers have not been widely implemented nor evaluated in prehospital environments. A recent study tested the intubation procedure performed by a cohort of paramedics with and without a containment box but was done in a study room and not within an ambulance patient module [34]. Further research on the prehospital environment is needed.

Several studies have published different methods to evaluate the efficiency of containment barriers. Some protocols include the use of fluorescent dyes measured with particle counters, aerosol particle size spectrometers, or photos in UV light [20,30,35]; black paint quantified with IMAGEJ image processing software [36]; smoke machines and picture collection [29]; fog machines and video recordings [25]; or the use of saline nebulizers and vapor generators with infrared thermography [24,29,37].

This study assessed an aerosol containment intervention within the patient module of an ambulance that is intended to decrease the risk of exposure to aerosols. The development of this protective intervention for ambulance use required consideration of the ambulance's unique characteristics such as limited space, storage, and limited working room. Adjunct (i.e., not built-in) interventions must be portable, easy to use, and positioned without hindering the EMS workers' activities. Based on these requirements a containment pod with a high efficiency particulate air (HEPA) filter extraction systems was evaluated as a local source-control intervention for containing aerosols during aerosol-generating procedures and removing them from the air before they could enter the ambulance module environment. Overall, the goal of this intervention was to provide additional protection to EMS providers, while also reducing the waiting time required for air exchange and cleaning to dilute and remove air contaminants (chemical and biological) during the transport of patients.

Materials and Methods

Air Containment and Filtration Interventions

Containment Pod with HEPA-Filtered Extraction Systems. One containment pod (IntubationPod, Under the Weather, Cincinnati, OH) (Fig. 1) was evaluated in conjunction with two different HEPA-filtered extraction units, each with a different airflow rate (80 cubic feet per minute (cfm) and 99 cfm). The combination of the pod and one of the HEPA-filtered extraction units was denoted as containment pod with HEPA-1 (CP-HEPA-1) (200 Series, Sentry Air System, Inc., Cypress, TX; Fig. 1(*a*)) while the combination of the containment pod and the other HEPA-filtered extraction unit was denoted as containment pod with HEPA-2 (CP-HEPA-2) (Omega, Atrix International, Inc., Burnsville, MN; Fig. 1(*b*)). The HEPA-filtered extraction units were chosen based on previous National Institute for Occupational Safety and Health (NIOSH) experience with the units given the size constraints of the ambulance and their rated airflow compared to other comparable units.

A durable plastic port made of acrylonitrile styrene acrylate plastic (MakerBot Industries, LLC) was three-dimensional

Table 1 Specifications and components of HEPA extraction units

Code	Filtration system	Dimensions (inches)	Airflow rating (cfm)	Pressure
Auxiliary HEPA	Custom-modified model UVC/HEPA-500HR Isolate, Corp., Houston, TX	13.34 (L) × 13.21 (W) × 18.86 (H)	235 cfm	NA
Containment pod (CP)	lntubationPod, under the weather, Cincinnati, OH	22(L) 19(W) × 22(H)	NA	NA
HEPA-1	200 Series, Sentry Air System, Inc., Cypress, TX Model: SF-200-FS	10.5 (L) × 8 (W) × 10.5 (H)	80 cfm	–0.012 in H_2O
HEPA-2	Omega Atrix International, Inc., Burnsville, MN Model: VACOMEGASECRU	20(L) × 6.25(W) × 9.25 (H)	99 cfm	–0.004 to –0.006 in H_2O

(3D)-printed (MakerBot Method, MakerBot Industries, LLC) and attached to the upper left side of the containment pod with Loctite 495 adhesive (Henkel Corporation). The two HEPA-filtered extraction systems had inlet ducts with different diameters of 2.54 cm (1 in.) (Atrix International, Inc.) and 7.62 cm (3 in.) (Sentry Air System, Inc.). Thus, port adapters were also 3D-printed such that both hoses could fit properly onto the containment pod port. The entire system including the containment pod and the HEPA extraction system had a length of approximately 208 cm (82 in.). The negative air pressure generated inside the containment pod using both CP-HEPA-1 and CP-HEPA-2 was measured with the manometer function of a ventilation meter (VelociCalc model 9565-P, TSI, Shoreview, MN). The pressure measurements and the properties of the system components are shown in Table 1.

Equipment and Instrumentation

Nebulizers. The nebulization protocol previously standardized by Mead et al. [38] was used for aerosol generation and is described below. The human-generated SARS-CoV-2 virus aerosol is usually carried by a mixture of water, saliva, mucus, and other air contaminants and can have a droplet size ranging from a few to several micrometers altogether [39,40]. To represent an aerosol size that will be influenced by air currents, have potential for remaining suspended for extended periods, and is associated with deep-lung penetration, 1.6 μm polystyrene latex (PSL) microspheres (4016A Monosized Particles, Thermo Scientific, Waltham, MA) with a particle density of 1.05 g/cm^3 and size distribution of $\pm$0.021 μm were used. The study used two medical nebulizers (Model 85B 0000, PARI Innovative Manufacturing Inc., Midlothian, VA) for aerosol generation [38]. To obtain a singlet PSL sphere droplet nuclei generation, the dilution of the PSL suspension was identified with the Otto Raabe equation and rearranged to obtain the singlet ratio (R) as shown below [38]:

$$R \cong 1 - \frac{F(MMD)^3 \cdot e^{4.5ln^2\sigma_g}}{y \cdot D^3} \cdot \left(1 - \frac{e^{ln^2\sigma_g}}{2}\right) \quad (1)$$

Here y is the dilution ratio (new volume/old volume) after suspension was diluted with pure liquid, R is the singlet ratio, F is the fraction by volume of particles in the original stock solution, MMD is the mass median diameter, σ_g is geometric standard deviation, and D is the diameter of the monodispersed spheres.

To solve the previous equation, the solution had an old volume of 1/12 mL per drop × 3 drops = 0.25 mL, and a new volume of 10 mL + old volume = 10.25 mL. Therefore, y was 10.25 mL/(0.25 mL) = 41.0. The fraction by volume (F) was 0.01, the MMD was 5 μm, a geometric standard deviation of 2.0, and the particle diameter was 1.6 μm. This resulted in an R of approximately 99% [38].

The nebulization protocol was standardized by generating a predominant aerosol size of 1–2 μm having less than 1% of agglomerates. The protocol consistently provided a uniform generation of particles. The study determined that 24 drops of 1.6 μm PSL microspheres in 80 mL of ultrapure distilled water (Gibco, Life Technologies Corporation, Grand Island, NY) provided the concentration for generating single droplets and reduced variability and instability of particle concentration [38]. This same protocol was followed for this study using two nebulizer pumps (Pari Vios, Pari Respiratory Equipment, Inc., Midlothian, VA) connected to nebulizer cups. Ten milliliters of the prepared PSL solution were poured into each nebulizer cup. Each day a new PSL solution (80 mL) was prepared and was used for up to four experimental trials. If additional experimental trials were performed, a new PSL solution was prepared.

The two nebulizers were placed near the mouth of a mannequin representing a patient and held in place using a piece of acrylic, threaded rod, and a custom 3D-printed adapter that allowed the height of the nebulizer to be adjusted along the length of the threaded rod.

Optical particle counters (OPCs). Four optical particle counters (OPCs) were used (model 11-D, GRIMM Aerosol Technik, Ainring, Germany) for particle concentration measurements. The OPCs logged an average particle concentration every 6 s. They operate at a standard flow rate of 1.2 L/min. The instruments use light scattering to detect individual particles and separate them into 31 size channels over the range of 0.253–35.15 μm. The GRIMM is reported to have a >97% reproducibility. For the current study, it was programed to report the data output as particle number concentration (particles/L) but the instrument can also provide data output as mass concentration (μg/m^3) if desired [41]. The bin size of interest for the current research was 1.545–1.821 μm, which included the PSL aerosol particle size (1.6 μm).

Four platforms of medium-density fiberboard and aluminum framing (80/20 Inc., Columbia City, IN) were fabricated by NIOSH engineers to place the OPCs at locations that approximate the breathing zone of EMS providers. The American Industrial Hygiene Association Engineering reference manual for anthropometric data was used to place the OPCs at the breathing zone level of a seated EMS worker. These data provide tables with height measurements for workstation design for women and men in the U.S. [42]. Since the EMS workforce is comprised of both genders, the measurements used were the 95th percentile for women and 50th percentile for men. For both populations, the sitting eye height and sitting knee height were essentially the same across genders. Therefore, the 95th percentile women's measurements were used. To obtain the breathing zone height, the sitting eye height (31 in., 78.74 cm) plus the sitting knee height (21.5 in., 54.61 cm) were added. Then 2 in. (5.08 cm) were subtracted from the total to obtain a mouth level. These criteria required the inlets of the OPCs to be 50.5 in. (128.27 cm) above the floor of the ambulance.

Ambulance. The intervention was evaluated in a type III ambulance (Wheeled Coach, Winter Park, FL). The ambulance was

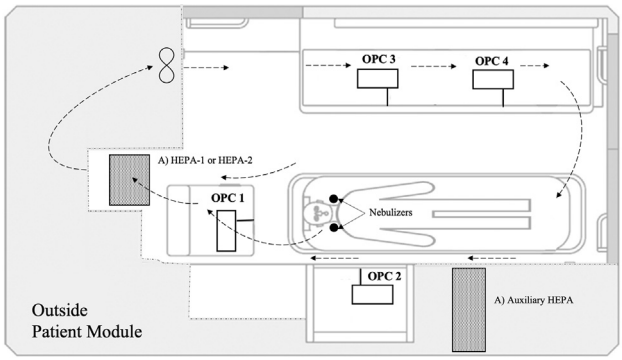

Fig. 2 Ambulance layout is shown. The containment pod with HEPA extraction systems (CP-HEPA-1 or CP-HEPA-2) is displayed. The auxiliary HEPA is permanently built into the ambulance patient module and was present in both layouts. The ambulance HVAC system is represented as a fan in the upper left of the patient module and recirculates as well as tempers the air within the patient module and the dotted arrows show the airflow direction. A mannequin is also observed on the patient stretcher with two nebulizer cups as the source for aerosol generation. Four OPC-1, OPC-2, OPC-3, and OPC-4 were placed in four locations inside the ambulance for data acquisition.

parked outside at the NIOSH facility located in Cincinnati, Ohio; and was connected to 120 V shoreline power during all experiments. The exterior openings of the patient module of the ambulance (excluding the doors) were sealed with aluminum foil tape before the experiments, including all exterior ports. The ambulance was prepared for testing in the following manner for all experiments: (a) the vehicle engine was turned on to power the cooling compressor within the HVAC system and (b) the HVAC fan system was turned on and set to the highest airflow setting with the thermostat set to 75 °F. Then, the nebulizer air pumps' power cords were routed through a port located at the side of the patient module so that the pumps could be turned on and off from the outside of the ambulance. A mannequin was placed on the patient stretcher. The nebulizer dosing cups were positioned on each side of the mannequin's face, at the same height as the mannequin's mouth. The OPCs were placed at each of the four locations (shown in Fig. 2) and were turned on to gather data for particle concentration. The ambulance doors were closed during data acquisition.

Temperature and relative humidity were also collected with HOBO H8 Pro-Series loggers (Micro-DAQ.com Ltd, Warner, NH) over the course of each trial to assist in troubleshooting any issue with the HVAC system. These data were not used in the assessment of the intervention. Temperature control was important for the airflow inside the patient module. The experiments in the module were conducted while the outdoor temperatures were equal to or higher than 68 °F (20 °C). Therefore, the HVAC system remained activated under cooling mode throughout each experimental trial.

The installation of a custom fit auxiliary HEPA filtration system (UVC/HEPA-500HR Isolate, Corp., Houston, TX) in the ambulance had been conducted during previous research and was kept the same and used for this study [3]. This auxiliary filtration system was only turned on when removing background particles but was turned off for the rest of the experiment and when CP-HEPA-1 or CP-HEPA-2 were tested.

Experimental Setup. The ambulance layout with the containment pod with HEPA-filtered extraction systems is shown in Fig. 2. Note that only one extraction system with the containment pod was used at a time. For safety reasons, the ambulance was not in motion while performing experiments. To meet safety requirements and to make sure the systems are secured inside the ambulance, any HEPA-filtered extraction system components used in a real-world environment would require means to secure them while in transit.

Experiments and Data Acquisition. The three experimental conditions evaluated were baseline and the two containment pod with HEPA-filtered extraction units (CP-HEPA-1 and CP-HEPA-2). The single-line diagram for all the experimental conditions is shown in Fig. 3 (a) baseline and (b) CP-HEPA-1 or CP-HEPA-2. The airflow is represented by the solid arrows and particles within the air were counted by the four OPCs. After data acquisition, the data were transferred to a computer for processing and analysis using SAS statistical software (Version 9.4, SAS Institute, Inc., Cary, NC).

There were 18 total trials evaluated, six trials of each of the three conditions. The order of all 18 trials was randomized. The order was not randomized in condition blocks, so successive trials of the same condition were allowed within the randomized order.

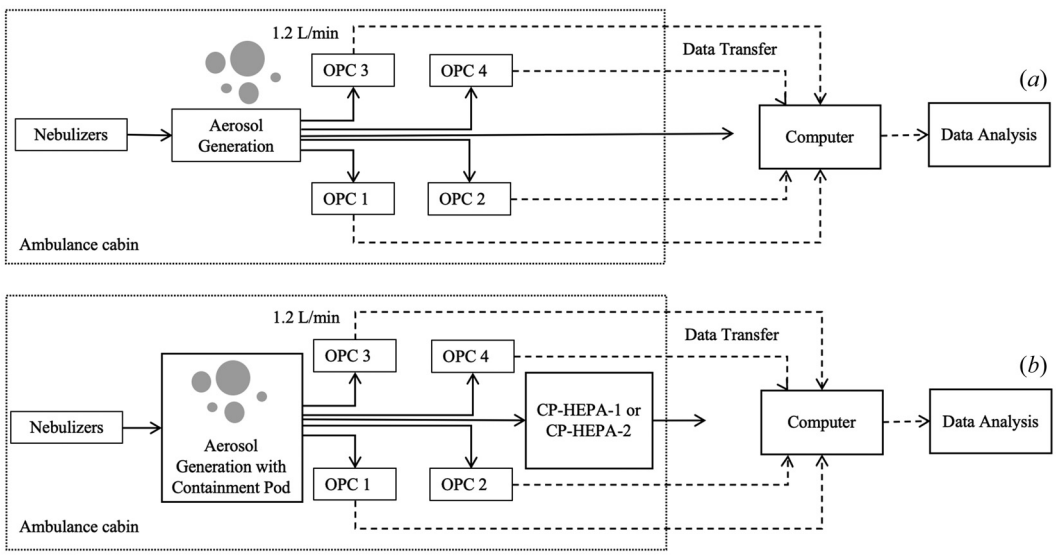

Fig. 3 Single-line diagrams of the experimental conditions: (*a*) baseline, and (*b*) CP-HEPA-1 or CP-HEPA-2. The airflow is represented by solid arrows and the particles are counted by the four OPCs at a sample volume of 1.2 L/min.

Table 2 Status of corresponding instrumentation for each experimental condition (baseline, and containment pod with HEPA-filtered extraction) during each phase

#Phase					Phase
1					Background particle removal
2					Stabilization
3					Aerosol generation
4					Decay (10, 20, 30 min)
Condition	#Phase	Recirculating system (HVAC)	Auxiliary HEPA	Nebulizers	CP-HEPA-1 or CP- HEPA-2
Baseline	1	On	On	Off	Off
	2	On	Off	Off	Off
	3	On	Off	On	Off
	4	On	Off	Off	Off
Containment pod with HEPA-filtered extraction systems	1	On	On	Off	Off
	2	On	Off	Off	Off
	3	On	Off	On	On
	4	On	Off	Off	On

Trials were conducted 4–5 times per day in the order of this randomized list. This randomized order across multiple days of evaluation allowed for random variability in which day each condition was evaluated and, therefore, reduced the influence of day-to-day climatic conditions and internal-external temperature differential on condition results.

Baseline. The protocol had four phases: (1) phase 1: auxiliary HEPA on to remove background particles, (2) phase 2: airflow stabilization period before aerosol generation, (3) phase 3: aerosol generation, and (4) phase 4: aerosol decay. In phase 1, the auxiliary HEPA was turned on for 15 min to assist in removing any aerosol that was already present in the cabin air. It was then turned off for the rest of the phases. In phase 2, the airflow and environmental conditions within the patient module were left to stabilize for 5 min. In phase 3, the two nebulizers were remotely turned on for 5 min of aerosol generation and then turned off. Finally, in phase 4 the aerosol concentration was left to decay for a period of 30 min. A complete experimental trial of the test protocol lasted 55 min. Six replicates ($n = 6$) of data were collected for each experimental condition. Table 2 shows the four phases and the on or off status of the corresponding instrumentation for each experimental condition.

Containment Pod with HEPA-Filtered Extraction Systems. For the containment pod test condition, the pod was placed before the beginning of the experiment covering the head of the mannequin and the nebulizer cups, and one of the HEPA-filtered extraction units was connected to the containment pod's extraction port. At the beginning of aerosol generation (phase 3), the HEPA extraction unit (CP-HEPA-1 or CP-HEPA-2) was turned on from outside the vehicle until the end of the experiment. Each test condition was evaluated six times ($n = 6$).

Data Analysis

Data Processing. The concentration of background particles was measured during the stabilization period during each replicate and averaged for each OPC on every test. Therefore, the averaged background removed each time was particular to each replicate and OPC. For each experimental trial, the average background particle concentration was subtracted from the particle data generated by the nebulizers during phases 3 (aerosol generation) and 4 (decay period). The area under the curve (AUC) of residual particle concentration of each OPC during all experiments was calculated. The trapezoidal rule was used for AUC calculations. For each test phase of each experiment, an overall patient module average concentration was calculated by obtaining the mean of the background-adjusted particle concentration for all four OPC locations.

The overall reduction percentages were also obtained for the baseline, CP-HEPA-1, and CP-HEPA-2 conditions. To eliminate background particles the following equations were used to obtain the relative increase and relative decay concentrations, and the overall percentage of reduction:

$$\text{Relative increase} = (\text{avg. particle conc. of phase 3}) - (\text{avg. particle conc. of phase 2}) \quad (2)$$

$$\text{Relative decay} = (\text{avg. particle conc. of phase 4}) - (\text{avg. particle conc. of phase 2}) \quad (3)$$

The overall percentage reduction was

$$\text{Overall percentage reduction} = \left[\frac{\text{relative increase} - \text{relative decay}}{(\text{relative increase})}\right] \text{x } 100\% \quad (4)$$

Statistical Analysis. The statistical analyses were conducted using SAS (Version 9.4, SAS Institute, Inc., Cary, NC), and one-way analysis of variance (ANOVA) with Tukey's multiple comparison tests performed with a 95% CI and a $p < 0.001$.

Qualitative Fog Test. A qualitative fog test was performed to visualize air flow within the containment pod and check for possible leakage from the containment pod. A C° breeze fog generator (Degree Controls Inc., Milford, NH) with propylene glycol-based fog solution was used. The fog generator was placed inside the containment pod and turned on for 30 s. The tests were performed both when CP-HEPA-1 and CP-HEPA-2 were operating to create negative air pressure and when they were not operational. All experiments were video recorded.

Results

The results are presented as overall averages of the four locations (OPC-1, OPC-2, OPC-3, and OPC-4) of six replicates of each test condition ($n = 6$).

Raw Data. The five-point moving average of the raw data obtained from the three conditions (baseline, CP-HEPA-1, and CP-HEPA-2) is presented in particles/L versus time showing all experimental phases (Fig. 4).

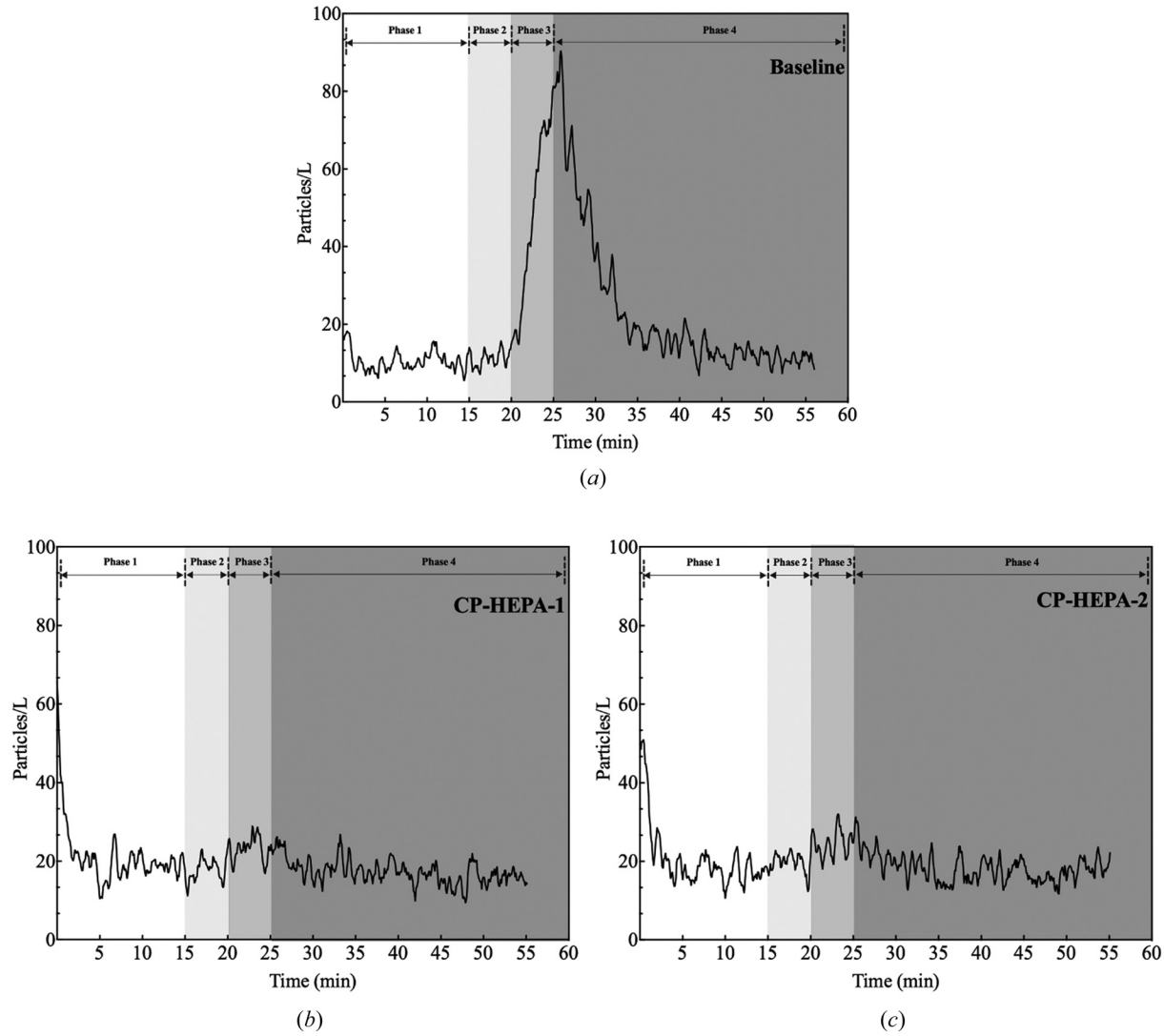

Fig. 4 The 5-point moving average of the raw data from the three experiments is shown in particles/L versus time: (*a*) baseline, (*b*) CP-HEPA-1, and (*c*) CP-HEPA-2. The different phases can be observed: phase 1 (auxiliary HEPA), phase 2 (stabilization), phase 3 (aerosol generation), and phase 4 (decay); ($n = 6$).

Baseline. For the baseline case, a peak concentration higher than 80 particles/L was observed at around 26 min in phase 3 while transitioning into phase 4 (Fig. 4(*a*)). During the first 5 min of phase 4, the baseline concentration decreased to ∼30 particles/L, with a final concentration being higher than 10 particles/L after 30 min.

CP-HEPA-1 and CP-HEPA-2. The containment pod with either HEPA-filtered extraction unit (CP-HEPA-1 and CP-HEPA-2) showed reduced peaks below 30 particles/L between a time range of 20–25 min during phase 3 (Figs. 4(*b*) and 4(*c*)), compared to the peak concentration of ∼80 particles/L of the baseline case during the same timeline (Fig. 4(*a*)).

Processed Average Particle Concentration of CP-HEPA-1 and CP-HEPA-2. Figure 5 shows the average particle concentration in particles/L during the aerosol generation and decay phases for the baseline, CP-HEPA-1, and CP-HEPA-2 conditions. Both CP-HEPA-1 and CP-HEPA-2, when used in combination with the containment pod, showed a reduction in average particle concentration to less than 20 particles/L during the aerosol generation phase compared to the 50 particles/L average during the aerosol generation phase for the baseline case ($p < 0.001$). Average particle concentrations remained in the range of 10–20 particles/L during all decay phases. Both CP-HEPA-1 and CP-HEPA-2 maintained ∼20 particles/L on average during the aerosol generation phase, although the baseline case reached the same concentration

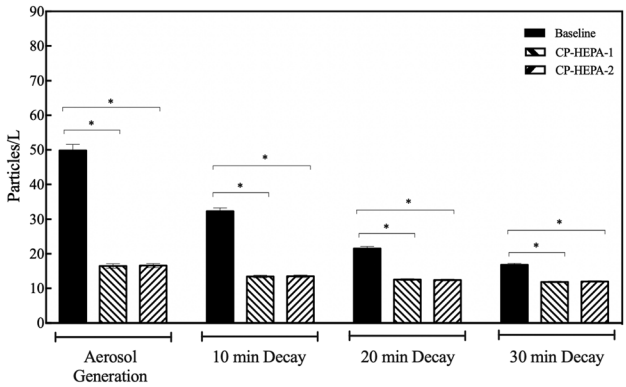

Fig. 5 Average particle concentration in particles/L during the aerosol generation and decay phases for the baseline, CP-HEPA-1, and CP-HEPA-2. One-way ANOVA was performed. Statistical differences are shown with an asterisk ($p < 0.001$); ($n = 6$).

Table 3 Mean particle concentrations (particle/L) and overall percentages of particle reduction for each condition during each phase

Condition	Stabilization phase mean (p/L)	Aerosol generation mean (p/L)	Relative increase: aerosol generation mean (p/L)	Phase 4: at 10 mia decay mean (p/L)	Phase 4: relative decay at 10 min Mean (p/L)	Phase 4: at 20 min decay Mean (p/L)	Phase 4: relative decay at 20 min mean (p/L)	Phase 4: at 30 min decay Mean (p/L)	Phase 4: relative decay at 30 min mean (p/L)
Baseline	8	50	50–8 = 42	32	32–8 = 24 Overall % reduction: 42–24/42 (100) = 42.8%	21	21–8 = 13 Overall % reduction: 42–13/42 (100) = 69%	17	17–8 = 9 Overall % reduction: 42–9/42 (100) = 78.5%
CP-HEPA-1	12	16	16–12 = 4	13	13–12 = 1 [b]	12	–[a] [b]	12	–[a] [b]
CP-HEPA-2	13	17	17–13 = 4	14	14–13 = 1 [b]	12	–[a] [b]	12	–[a] [b]

[a]Decay mean aerosol counts less than or equal to the stabilization phase's mean background count are shown as "–".
[b]% reduction does not apply. Neg. pressure containment pod prevented aerosol escape into ambulance patient module.

after 30 min of decay. The CP-HEPA-1 and CP-HEPA-2 reduced the particle concentration significantly during all phases when compared to the baseline case ($p < 0.001$). No statistical difference was observed between CP-HEPA-1 and CP-HEPA-2 during the aerosol generation and the decay phases ($p < 0.001$). Therefore, both CP-HEPA-1 and CP-HEPA-2 performed equally well at controlling overall aerosol concentrations within the ambulance module.

Overall Percentage Reduction of Particle Concentration. The overall percentage of reduction of baseline was obtained and is shown in Table 3. Background particle concentrations were present during the stabilization phase (phase 2). The equations to remove the background particle concentrations and to obtain the overall percentages of reduction are shown in the methods section (Eqs. (2)–(4)). All the calculations are shown in Table 3.

After 10 min the baseline case had an approximate relative aerosol reduction of 43%, at 20 min of 69%, and after 30 min of 79% (Table 3). An example calculation is presented below.

Calculations for the baseline case at 10 min

$$\text{Relative increase} = (50) - (8) = 42\,\text{particles/L}$$

$$\text{Relative decay at 10 min} = (32) - (8) = 24\,\text{particles/L}$$

$$\text{Overall percentage reduction} = \left[\frac{42 - 24}{(42)}\right] \text{x } 100\% = 42.8\%$$

Fog Test Observations. The CP-HEPA-1 had a filtered airflow rating of 80 cfm while CP-HEPA-2 had a rating of 99 cfm. When the containment pod with filtered extraction units were operating, the fog plumes were observed at the fog-generator's outlet only. Leakage of fog was observed outside the pod when the HEPA-filtered extraction systems were not operating. This showed visually the protective effect provided by the negative air pressure in the containment pod, relative to the cabin, in preventing aerosol migration.

Discussion

This study evaluated an intervention that uses containment and filtration to reduce aerosol concentrations inside the patient module of an ambulance. Aerosol concentration measurements were obtained using OPCs and an aerosol surrogate to mimic a real-life exposure scenario. The containment pod with the HEPA-filtered extraction units worked as a local source containment and extraction zone within the patient module. This containment approach reduced the concentration of source aerosol within the patient module during the aerosol generation phase. The negative pressure and filtration generated by the HEPA extraction units ensured that the aerosol stayed contained until it was mitigated. Thus, the pod with extraction units allowed for reduction of the aerosol peak and overall concentration during the aerosol generation phase, both of which are important factors in regard to infectious aerosol dissemination. The aerosol and fog tests both helped confirm the importance of the containment pod with HEPA-filtered extraction units for improved protection from exposure to the source aerosols.

Although there was no statistical difference in performance between CP-HEPA-1 and CP-HEPA-2, there were differences in negative air pressure. CP-HEPA-1 had a negative air pressure of –2.98 Pa (–0.012 in H_2O), while CP-HEPA-2 had between –0.99 Pa to –1.49 Pa (–0.004 to –0.006 in H_2O). CP-HEPA-1 had a 7.62 cm (3-in.) hose and a rated airflow of 80 cfm with the HEPA filter installed. CP-HEPA-2 had a higher airflow (99 cfm) but smaller hose diameter (2.54 cm [1 in.]). It is possible that the HEPA filter units were operating at different airflow rates than the specifications provided by the manufacturer, due to the experimental adapters used to connect them to the containment pod. However, the flowrates used for the containment pod appeared to meet or exceed that required to maintain containment; therefore, the results obtained were not significantly different.

Background Aerosol Contamination. The auxiliary HEPA filter was used to reduce background particles before the experiments. Nevertheless, higher-than-expected infiltration, environmental sources such as adjacent train tracks, and diesel exhaust from the ambulance engine might have combined with mixing inefficiencies within the module itself to impact the level to which background particles could be reduced. It is also possible the elevated particles before phase 1 were generated during the pretest experimental setup. This could explain the high concentration of particles/L before phase 1 while also increasing variability among experiments. Additionally, at the end of each experiment, the ambulance's doors were opened to retrieve the data from the OPCs, increasing the environmental aerosols in the patient module from the outside air. To mitigate this variability in particle concentration between experimental trials, the auxiliary HEPA filter was operated for 15 min before each experiment (phase 1). It was previously determined that turning on the auxiliary HEPA filter for 15 min reduced the particle concentration inside the patient module to its minimum, leading to stabilization of particle concentration.

A consistent, low-level concentration of particles was still present during all experiments, as indicated in the stabilization period. Therefore, the background levels of particle concentrations needed to be subtracted from all datasets to correct for this background. The infiltration of background particles could be

attributed to: (a) the custom-installed auxiliary HEPA filter and fan unit inducing airflow leakage into the patient module from outside through leaks in the airflow route during operation of the ambulance HVAC system, (b) small, unseen openings in the ambulance envelope, and (c) inadequate mixing within the ambulance patient module, preventing uniform filtration of existing particles.

Future testing could be done in a more controlled indoor environment while removing background aerosols under variable environment conditions. Additional tests could be performed when outdoor temperatures are cooler, and the HVAC system of the ambulance is in heating mode. The containment pod with extraction units could be further evaluated with bioaerosols generated in a more natural manner. Ultimately, this intervention could be tested in ambulances with actual EMS workers within ambulances during realistic transportation scenarios.

Conclusions

This investigation showed that a containment pod with HEPA-filtered extraction can contain and reduce aerosol concentrations within the ambulance patient module and thus reduce worker exposures to potentially infectious bioaerosols. The containment pod with HEPA-filtered extraction was shown to successfully contain surrogate test aerosol during the generation phase, thus eliminating peak exposures and minimizing aerosol spread throughout the patient module. The negative pressure within the containment pod, generated by the HEPA-filtered extraction units, facilitated the containment of the test aerosol while removing the concentration from within the pod itself (as demonstrated by the fog test). Collectively, the evaluated intervention functioned as a local source control and extraction system that reduced aerosol concentrations in the ambulance patient module throughout the evaluated test sequence. Future studies could include evaluating the system under the same experimental setup using bioaerosols instead of surrogates for a more realistic scenario.

Author Contributions

Pena helped with the conceptualization, methodology, investigation, data curation, original draft preparation, review and editing; Neu helped with the methodology, investigation, data curation, original draft preparation, review and editing; Feng helped with data curation; Hammond helped with the methodology, investigation, review and editing of the original draft; Mead helped with the methodology, investigation, review and editing of the original draft; Banerjee helped with the conceptualization, methodology, investigation, review and editing the original draft. All authors have read and agreed to the published version of the paper.

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Conflicts of Interest

The authors declare no conflict of interest.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

Disclosure statement

The authors report no financial relationships or conflicts of interest regarding the content herein.

Nomenclature

ANOVA = analysis of variance
CDC = centers for disease control and prevention
CP-HEPA-1 = containment pod with HEPA-1
CP-HEPA-2 = containment pod with HEPA-2
EMS = emergency medical service providers
EPA = Environmental Protection Agency
FDA = Food and Drug Administration
HEPA = high efficiency particulate air filter
HVAC = heating, ventilation, and air cleaning systems
NIOSH = National Institute for Occupational Safety and Health
OPC = optical particle counters

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