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Original Article

Aerosol and surface contamination assessment of a novel ventilated infectious aerosol containment device

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Abstract

Healthcare personnels (HCPs) are at risk of respiratory infectious diseases during patient care activities. HCPs rely primarily on personal protective equipment to prevent pathogen exposures, but there is a need to develop alternative, or complementary control strategies, including engineering controls. The objective of this study was to evaluate the ability of the 3 designs (denoted D_{1A}, D_{1B}, and D_2) of the University of Utah Containment Ventilation for Exposure Reduction (U-COVER), a protective barrier enclosure device to contain respirable aerosols when placed over a simulated patient. The 2 primary performance metrics were the percent reduction in: (i) the concentration of respirable aerosols in the simulated breathing zone of an HCP, and (ii) surface contamination outside the device, which were tested using salt aerosols and fluorescein aerosols, respectively. Briefly, salt or fluorescein aerosols were generated as though expelled by a prone patient under 3 conditions: (i) no device (control), (ii) with the device but without exhaust ventilation, and (iii) with the device with exhaust ventilation. Device D_2 was also tested under simulated use conditions, in which cardboard "arms" were placed inside the device ports. All 3 device designs showed the ability to reduce particle concentrations in the simulated HCP breathing zone and on surfaces by >99% with exhaust ventilation compared to the control condition. Without exhaust ventilation, device performance was lower and highly variable. Under simulated use conditions, device D_2 reduced particle concentrations in the simulated HCP breathing zone by ≥91% and on surfaces by >99% relative to control for all combinations of "arms" tested. The U-COVER device demonstrates excellent aerosol containment and warrants further testing with dynamic simulated or actual use conditions.

Key words: bioaerosol; exposure; healthcare; respirable dust; ventilation.

What's Important About This Paper?

This study investigates a different strategy to supplement the conventional dependence on personal protective equipment to reduce the risk of infectious disease transmission to healthcare professionals (HCPs). The study found that a ventilated aerosol containment device termed the U-COVER, reduces aerosol concentration by more than 99% in the breathing zone of HCP and on surfaces. The device functions well even under simulated use conditions. Further research into these engineering controls may result in a more secure workplace for HCPs, improving patient care while halting the spread of contagious diseases.

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Introduction

The transmission of respiratory infectious diseases like COVID-19 and influenza is an important ongoing concern for healthcare personnel (HCP) (Wilson et al. 2022). In the first 2 mo of the COVID-19 pandemic, more than 9,000 HCPs were diagnosed with the disease, and most of these cases likely arose from workplace exposures (Kambhampati et al. 2020). Occupationally acquired COVID-19 infections have been a global problem, with the WHO estimating 115 500 deaths among HCPs between January 2020 and May 2021 (WHO 2020). Even when there is a relatively low disease burden in a community, HCPs remain at risk due to the nature of their work. Aerosol-generating procedures (AGPs) are thought to be an important source of exposure to respiratory pathogens among HCP, and such procedures include, but are not limited to: nebulizer treatments, bilevel positive airway pressure (BiPAP) ventilation, endotracheal intubation, and bronchoscopy (Jackson et al. 2020). It should be noted that the concept of "aerosol-generating procedures" is currently under discussion within the public health community (Klompas et al. 2021; Wilson et al. 2021; Leal et al. 2022; Silvers et al. 2022). This is due, in part, to increasing evidence that simple actions like coughing and routine patient care activities can also generate infectious aerosols.

In healthcare settings, personal protective equipment (PPE) is a primary strategy to prevent occupational exposure to pathogens (Siegel et al. 2007). The hierarchy of controls used in occupational health, however, prioritizes engineering and administrative controls over PPE. During the COVID-19 pandemic, in part owing to the shortage of PPE, there was a surge in interest in developing engineering controls to prevent COVID-19 transmission and environmental contamination in healthcare facilities. One such engineering control is a "box" or "tent" placed over the head and torso of an infectious patient to contain, and in some designs remove, respiratory aerosols emitted from the patient (Maniar and Jagannathan 2020). As reviewed by Jones *et al.* (2023), these aerosol containment devices have been subject to varied, and generally limited, testing of usability and aerosol containment. Although some data do exist on the aerosol containment performance of such devices (e.g. Fidler et al. 2021), more robust device testing is required to support device integration into clinical practice, including testing under simulated or actual use conditions such as accessing the patient through device ports could significantly alter aerosol containment performance. During the COVID-19 pandemic, the FDA issued a warning about the risks associated with using passive protective barrier enclosures without negative pressure systems, further emphasizing the need for carefully designed and tested solutions like the U-COVER device (U.S. Food & Drug Administration (FDA) 2020).

This work is part of a user-centered design approach to evaluating and improving an aerosol containment device initially developed by investigators at the University of Utah Center for Medical Innovation (Brant-Zawadski et al. 2021). The initial device design (D_0) involved a flexible aluminum frame with a loose plastic drape, which could be equipped with a vacuum fan fitted with a HEPA filter to remove aerosols. Based on motion capture studies and user feedback, a second design iteration was built (D_{1A} and D_{1B}), which features a more fitted plastic drape and increased dimensions than D_0. D_{1A} and D_{1B} have the same overall shape but differ in the configuration of the rigid aluminum frame (Fig. 1). A third design iteration (D_2) was then created utilizing a slightly altered frame and the addition of: (i) rigid rings encircling the arm ports and (ii) a new, smaller ventilation fan that was affixed to the side of the device, the placement of which was based on computational fluid dynamics simulations (Fig. 1). Preliminary work has shown that the original device design has the potential to effectively reduce HCP exposure to infectious droplets and aerosolized particles (Brant-Zawadski et al. 2021). The goal of this study was to rigorously evaluate the aerosol containment performance of the University of Utah Containment Ventilation for Exposure Reduction (U-COVER, a protective barrier enclosure) device designs D_{1A}, D_{1B} and D_2. Specifically, our objectives were to: (i) assess the device's ability to reduce HCP exposures to respirable aerosols, (ii) assess the device's ability to reduce contamination of surfaces, and (iii) assess the device's ability to maintain efficiency with simulated usage. The latter was used because it was hypothesized that opening the ports to use the device may decrease the containment performance.

Methods

U-COVER device

Three similar U-COVER device designs were tested in this study (Fig. 1). Design D_{1A} and D_{1B} had a rigid aluminum frame, in slightly different configurations, with a fitted plastic drape. These were identical in their overall dimensions, measuring 0.5 m in length, 0.55 m in width, and 0.45 m in height. Arm ports consisted of slits cut into the drape. Design D_2 had a similar geometry, but a slightly altered aluminum frame design and the access ports were encircled by rigid plastic circles. This design was the same length and width as the previous ones but had a height of 0.49 m. The device can be used with and without active local exhaust ventilation. Designs D_{1A} and D_{1B} included a variable flow control fan (Part No. 9SG5724P5H61, Sanyo

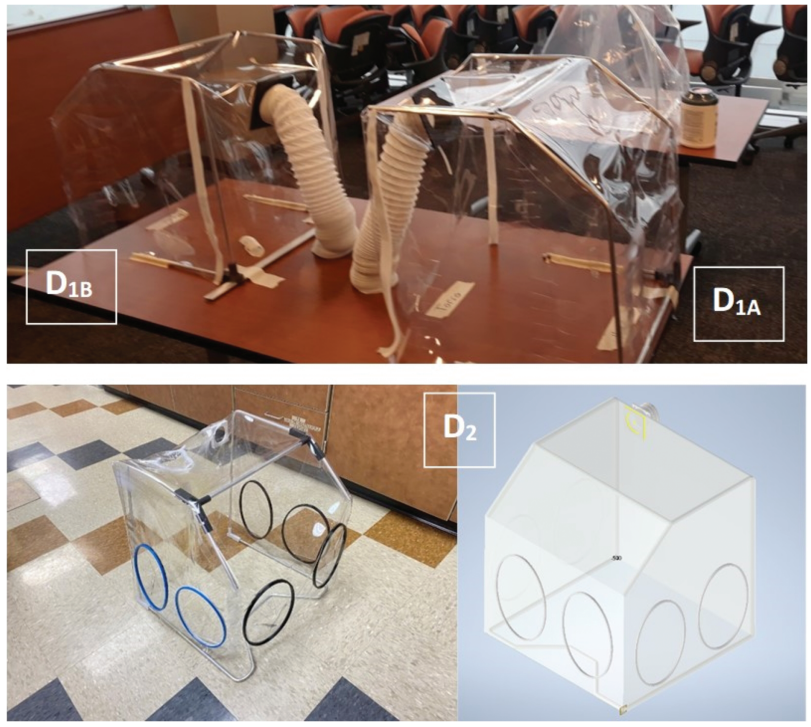

Figure 1. Three design iterations of the U-COVER device: D_{1A} (above right), D_{1B} (above left), D_2 (bottom).

Denki America Inc., Torrance, California), while design D_2 had a fixed flow ventilation system (Part No. PF80381BX-000U-S99, Sunon Fans, Brea, California). A different fan was chosen for design D_2 so that it could be attached directly to the hood, rather than connected to the hood via a flexible duct. Preliminary testing with designs D_{1A} and D_{1B} suggested that airflow could be reduced without affecting containment (data not shown), so for D_2 a smaller fan that utilized less energy was selected. All 3 designs exhaust air through a high-efficiency particulate air (HEPA) filter. Noise levels were measured for each device using an octave band analyzer and shown to be between 72 and 74 dBA for all designs.

Experimental set-up

All experiments were performed in the Industrial Hygiene Research Laboratory at the University of Utah from November 2021 to November 2022. A temporary testing chamber was constructed (1.45 m × 1.3 m × 1.68 m high) using heavy-weight plastic sheeting draped from the ceiling to a laboratory bench. In all tests, the U-COVER device was placed over an adult upper-body mannequin task trainer (Prestan Products, Mayfield, Ohio). Tests that involved a simulated user included cardboard "arms" inserted into 1 or more sets of access ports so as to assess aerosol containment when the seal of the device is "broken" by the HCP accessing the patient. Experimental conditions are summarized in Table 1.

The first round of testing, denoted baseline testing in Table 1, involved 2 (n = 2) different aerosols to evaluate aerosol containment and surface contamination. These were conducted using each device (D_{1A}, D_{1B}, and D_2, n = 3) under 3 different conditions (n = 3): (i) no device present, (ii) device without exhaust ventilation, and (iii) device with exhaust ventilation. Each set of conditions was tested in triplicate. To minimize cross-contamination of experimental equipment, for each device generation, aerosol containment tests were performed first, followed by surface contamination experiments.

The second round of testing involved simulated use tests with device design D_2 only. The U-COVER device has 6 ports through which an HCP can insert their hands/arms: 2 near the patient's head, 2 on the patient's left side, and 2 on the patient's right side. The ports are normally closed (but not sealed) until the HCP inserts an arm or other item into the port. Seven configurations representing all permutations of the simulated arm pairs were tested: (i) 2 arms, front only, (ii) 2 arms, right only, (iii) 2 arms, left only, (iv) 4 arms, front and right, (v) 4 arms, front and left, (vi) 4 arms, right and left, and (vii) 6 arms, front, left, and right.

Table 1. U-COVER device information and experimental conditions.

	Design D_{1A}	Design D_{1B}	Design D_2
Containment features			
Volume (m^3)	0.125	0.125	0.135
Ventilation location	Central	Central	Left
Ventilation air flow rate (m^3/min)	2.12	2.12	1.81
Air exchange rate (/h)	1,017	1,017	804
Experimental parameters			
Baseline testing[a]	Y	Y	Y
Control: no device	Y	Y	Y
Device: no exhaust ventilation	Y	Y	Y
Device: with exhaust ventilation	Y	Y	Y
Simulated usage assessment[a]	N	N	Y
Control 1: no exhaust ventilation for aerosol test	N	N	Y
Control 2: no device for surface test	N	N	Y
Device: with exhaust ventilation	N	N	Y

[a]Tests were performed with respirable salt aerosol and fluorescein aerosol.

Aerosol containment and surface contamination were tested for all 7 arm configurations, and all the testing of simulated usage was also performed in triplicate.

Relative humidity and temperature were recorded at the start of each experiment. At the start of each experiment involving ventilation, the fan inlet velocity was measured with a VelociCalc 9565 Air Velocity Meter (TSI, Shoreview, Minnesota). For those experiments, the ventilation of design D_{1A} and D_{1B} were maintained at an airflow rate of 2.12 m^3/min, which was the maximum setting on that fan. For design D_2 the fan had a fixed air flow rate of 1.81 m^3/min.

Respirable salt aerosol containment

Aerosol containment was evaluated using salt aerosols in the respirable size range (<5 µm). Aerosols were generated using 5 mL of a salt solution (625 mg of NaCl dissolved in 750 mL deionized water and 250 mL isopropyl alcohol) injected into a Blaustein Atomizing Module (CH Technologies, Westwood, New Jersey) at the rate of 1 mL/min (over 5 min) using an automated push/pull syringe pump (New Era Pump Systems Inc., Farmingdale, New York) and with compressed air at 10 psi. Velocity at the atomizer was ~4 m/s. The operating velocities of the particle generation system were intended to be roughly within the range which could be generated from a person's upper respiratory tract through breathing or coughing (Kwon et al. 2012).

Particle concentrations were measured using 2 GRIMM Model 1.109 Portable Aerosol Spectrometers (Grimm Technologies Inc., Douglasville, Georgia): one was positioned inside the device in the breathing zone of the task trainer, and the other outside the device in the simulated breathing zone of an HCP standing at the head of a patient. The GRIMM has a specified measurement range from 0.25 µm to 31 µm and reports particle counts in 32 size bins over this size range every 6 s. The samplers were turned on before aerosol generation started and were operated until the 5-min aerosol-generating process finished. The particle size distributions measured inside the device and during control tests are included in the Supplemental material (see Fig. S1). The count median diameter was between 0.3 and 0.35 µm with a geometric SD between 1.43 and 1.67.

Fluorescein aerosol containment

Surface contamination studies used a fluorescein aerosol. Aerosols were generated using 25 mL of a fluorescein solution (500 mL of 106 µg/L fluorescein in sodium phosphate buffer, 500 mL isopropyl alcohol, and 13 mL oleic acid) injected into a Blaustein Atomizing Module (CH Technologies, Westwood, New Jersey) at the rate of 5 mL/min (over 5 min) using an automated push/pull syringe pump (New Era Pump Systems Inc., Farmingdale, New York) and with compressed air at 25 psi. Velocity at the atomizer was ~20 m/s. In contrast to the salt aerosol tests, a higher velocity and volumetric flow rate for fluorescein was chosen to allow for the collection of enough fluorescein on sampling media. After aerosol generation, particles were allowed to settle for 5 min. Settled fluorescent material was collected on 8-in squares of aluminum foil placed at 8 sampling locations around the exterior

perimeter of the U-COVER device (see Supplemental material, Fig. S2). Aluminum foil was chosen because it showed high extraction efficiency in preliminary method development. After the 5-min settling period, a fan with a HEPA filter was placed within the experimental chamber to reduce suspended particulates. Particles were allowed to settle for 5 min based on preliminary experiments that suggested sufficient settling of fluorescein particles within this period under the specific experimental conditions used. However, it is important to note that aerosol settling times can vary widely depending on particle size and ventilation, and the selected 5-min duration may not be representative of all aerosol types or conditions. All sampling media was immediately removed from the chamber, placed into sample collection bags, labeled, and stored away from UV light until analysis. Two blank samples were processed for each experimental trial.

For fluorescein extraction, a 20 mL volume of phosphate buffer solution was first added to sample collection bags. This volume of phosphate buffer solution was determined prior to experimental trials to ensure that the concentration of each sample was <250 µg/L. Next, the bag was shaken to mix the contents evenly, and then the extraction solution was put into a Pyrex tray and the sample media was agitated for 30 s. Fluorescein concentration was then analyzed using a benchtop fluorometer calibrated with a 5-point calibration curve ($R^2 > 0.99$) (Trilogy Designs, Sunnyvale, California). The method detection limit (MDL) was determined to be 0.034 µg/L using the Environmental Protection Agency (EPA) methodology in 40CFR136 Appendix B (EPA 1977). To prevent cross-contamination of fluorescein within the buffer solution and during fluorometric analysis, samples were prepared, stored, and analyzed in a separate lab from where the experimental tests were performed. Samples were measured in duplicate with the fluorometer to determine fluorescein concentration (µg/L) and then averaged to obtain the final result.

Data analysis

Salt aerosol data collected by the GRIMM devices were collapsed into 3 size ranges: (i) $d_p \leq 0.35$ µm, (ii) 0.35 µm < $d_p \leq 1$ µm, and (iii) 1 µm < $d_p \leq 5$ µm; particles with $d_p > 5$ µm were excluded because negligible numbers were measured. Time trends were explored graphically, and the time-averaged concentrations during the 5-min aerosol generation period were tabulated for each experimental replicate. Summary statistics were tabulated for each experimental condition. The primary outcome was the percent reduction in the time-averaged aerosol concentration at the location representing the HCP's breathing zone for the device conditions (ventilated and nonventilated) relative to the control condition (no device), for each device design. This analysis best represents the change in exposure to the worker when using the device compared to when the device is not present. This was calculated for each size bin, and for all particle sizes combined. Background correction of particle counts for each trial was not applied because background particle counts were equal to <0.25% of the particle counts during the control trials. Data were downloaded from the GRIMM devices and saved in Microsoft Excel files.

For surface contamination tests, fluorescein concentrations < MDL were replaced by the MDL divided by the square root of 2. Measured fluorescein concentrations were converted to nanograms per square inch (ng/in^2) and summary statistics were tabulated for each sampling location and experimental condition. The primary outcome was the percent change in mass of fluorescein at each sampling location for the device conditions (ventilated and nonventilated) relative to the control conditions (no device), for each device design.

Data analyses were performed using the R Project for Statistical Computing and Microsoft Excel (R Core Team 2021).

Results

Respirable salt aerosol containment

Summary statistics for the time-averaged particle concentrations measured at the simulated HCP breathing zone are shown in Table 2. Overall, all 3 device designs performed similarly when the ventilation system was operating, yielding a reduction in particle concentrations in the simulated breathing zone of >99% when considering all particle counts combined and for each particle size bin. When the device was operated with the integrated ventilation system turned off, the exposure reduction was smaller and more variable. In that case, designs D_{1A} and D_{1B} saw 43.08% and 47.79% reduction on average, respectively, for all particle sizes. Design D_2 performed slightly better without any ventilation, showing a reduction of 66.24% for all particle sizes, on average.

Fluorescein aerosol containment

Summary statistics for the fluorescein mass concentration quantified on surface samples outside the device are shown by sampler location in Table 3. During control trials with no device present, the highest fluorescein concentrations were found at locations along the right side of the mannequin, and these were an order of magnitude higher on the right at the patient's waist and torso than on the left. This pattern was present when the devices were tested with and without ventilation, but was less pronounced.

Table 2. Mean and SD of time-averaged particle count concentrations (#/L), measured in the simulated HCP breathing zone, and the percent reduction in concentration relative to the control condition (no device).

Particle size bin[a]	Design D_{1A}		Design D_{1B}		Design D_2	
	Mean (SD) particle count conc.	Mean (SD) percent reduction	Mean (SD) particle count conc.	Mean (SD) percent reduction	Mean (SD) particle count conc.	Mean (SD) percent reduction
Control						
1	39 700 (20 100)		40 100 (18 500)		41 100 (145 900)	
2	18 700 (11 000)		18 200 (9,330)		16 900 (6,870)	
3	1,180 (748)		1,040 (58)		1,060 (39)	
Total	59 700 (31 800)		59 300 (2,830)		59 100 (22 004)	
No ventilation						
1	23 000 (26 150)	42.21% (2.42)	21 000 (2,510)	47.65% (0.62)	11 300 (9,820)	67.01% (0.23)
2	10 500 (13 700)	44.12% (1.86)	9,620 (12 600)	47.09% (0.99)	4,320 (4,200)	63.94% (0.36)
3	533 (772)	54.85% (1.44)	443 (614)	57.50% (0.59)	186 (21)	73.35% (0.20)
Total	34 000 (40 500)	43.08% (0.68)	31 000 (38 200)	47.79% (0.64)	15 800 (1,420)	66.24% (0.24)
Exhaust ventilation						
1	126 (76)	99.74% (2.34)	210 (144)	99.48% (0.004)	59 (30)	99.88% (0.001)
2	22 (15)	99.88% (1.63)	35 (21)	99.81% (0.002)	13 (11)	99.96% (0.001)
3	3 (4)	99.71% (1.23)	6 (7)	99.42% (0.007)	5 (14)	99.56% (0.013)
Total	151 (85)	99.74% (0.60)	251 (163)	99.57% (0.003)	77 (42)	99.84% (0.001)

[a]Bin 1: $d_p \leq 0.35$ µm, bin 2: $0.35 < d_p \leq 1$ µm, bin 3: $1 < d_p \leq 5$ µm.

When the devices were used without ventilation, the reduction in surface contamination was highly variable between replicates and in some cases showed no decrease (Table 3). The average reduction in surface contamination was –4.7%, 15.4%, and 52.9% for designs D_{1A}, D_{1B} and D_2, respectively. When exhaust ventilation was operating, all device designs reduced surface contamination by >99%, with low variability among replicates.

Impact of simulated use

Summary statistics for the time-averaged respirable salt aerosol count concentrations measured during the simulated usage tests are shown in Table 4. When the ports were activated, the device showed a decrease in aerosol concentration in the simulated breathing zone of the HCP by ≥ 91%. This is in contrast to the tests without ports activated, where the reduction was >99% (Table 2). However, it is important to note that under specific conditions, namely for low concentrations of the largest particle sizes, the percentage reduction could potentially decrease to around 80%. Poorer performance was not necessarily associated with an increased number of ports in use, or with the locations of port use. In the fluorescein aerosol tests, all of the simulated use conditions maintained a >99% reduction in surface contamination outside the device (Table 5), which is similar to the baseline tests (Table 3).

Discussion

Inhalation of respirable aerosols and contact with contaminated surfaces are well-known exposure pathways for respiratory pathogens such as SARS-CoV-2

Table 3. Blank corrected mean and SD fluorescein mass concentration (ng/in^2) and the percent reduction in concentration relative to the control condition (no device).

Sampling location[a]	Mean (SD) fluorescein concentration (ng/in^2)						
	Control	No ventilation			Exhaust ventilation		
		Design D_{1A}	Design D_{1B}	Design D_2	Design D_{1A}	Design D_{1B}	Design D_2
A1	901 (116)	704 (387)	1,310 (367)	351 (88.1)	0.28 (0.29)	0.04 (0.04)	0.39 (0.24)
A2	1,160 (155)	930 (355)	641 (152)	592 (45.3)	0.23 (0.36)	0.07 (0.05)	0.41 (0.31)
B1	622 (49.7)	177 (81.7)	500 (255)	135 (36.1)	0.12 (0.11)	0.02 (0.03)	0.18 (0.11)
B2	1,640 (199)	617 (149)	341 (30.8)	458 (12.3)	0.97 (0.24)	0.08 (0.14)	0.64 (0.29)
C1	584 (54.7)	316 (78.0)	728 (240)	280 (5.69)	0.26 (0.30)	0.06 (0.10)	0.29 (0.16)
C2	1,060 (145)	3,200 (893)	1,320 (206)	1,010 (82.4)	0.59 (0.48)	0.79 (1.36)	0.15 (0.11)
D1	621 (49.0)	327 (32.6)	402 (76.3)	182 (11.5)	0.06 (0.06)	0.10 (0.12)	0.13 (0.12)
D2	776 (62.1)	1,250 (256)	697 (247)	367 (50.7)	0.04 (0.03)	1.61 (2.62)	0.03 (0.03)
	Mean (SD) percent (%) reduction						
All		0 (96.1)	15.37 (46.1)	52.89 (35.2)	99.96 (0.03)	99.96 (0.12)	99.97 (0.03)

[a]A1: left, patient head; A2: right, patient head; B1: left, patient shoulder; B2: right, patient shoulder; C1: left, patient torso; C2: right, patient torso, D1: left, patient waist; D2: right, patient waist.

or influenza. This study demonstrated that when the U-COVER device was operated with ventilation, it provided a >99% reduction in respirable aerosol concentrations in the breathing zone of an HCP, and a >99% reduction in surface contamination around the outside of the device (Tables 2 and 3). When HCP usage was simulated through the access ports, the device's effectiveness in reducing respirable aerosol concentrations in the HCP's breathing zone ranged from 91% to 99% (Table 4). However, the efficiency in minimizing surface contamination consistently remained >99% regardless of the number and location of HCP users (Table 5).

Overall, design D_2 performed better than designs D_{1A} and D_{1B} in both containment assessment tests. Design D_2 has a different fan, with a slightly lower air flow rate (1.81 m^3/min versus 2.12 m^3/min), and a different fan placement that was selected based on fluid dynamics simulations. Even without exhaust ventilation supplied, design D_2 performed better more consistently and with a greater percent reduction in aerosol concentrations and surface contamination than D_{1A} and D_{1B}, which may be due to improved tightness of the device cover and port design that limited gapping. This design of ports is challenging because they need to be flexible enough to permit rapid entry and removal of hands and equipment by HCP, but remain closed when not in use.

Given the more well-developed design of D_2, only that version was used to investigate simulations of HCPs using one or more of the access ports. Although the aerosol containment was slightly reduced during simulated usage (>91% versus >99%), the surface contamination was still reduced by 99% regardless of the number or locations of ports used. In combination, this highlights the ability of such a device to reduce HCP exposure to infectious aerosols through several potential exposure pathways.

Other studies have assessed the containment performance of similar devices with aerosols and surface contamination using a fluorescent material as a surrogate for infectious material generated through the upper airway of a patient lying prone (Fried et al. 2020; Lumlertgul and Inboriboon 2021). And, there have been additional studies that utilized other testing methods, performance metrics, and ways in which the device was incorporated into medical procedures (Cottrell et al. 2020; Ibrahim et al. 2020; Jones et al. 2022). Importantly, none of the existing publications, to our knowledge, have performed simulation experiments related to HCP usage. The results presented here provide further evidence that aerosol and surface contamination by respiratory aerosols can be substantially reduced when using such an aerosol containment device.

Similar to the findings presented here, Daniel et al. discovered a 99% decrease in aerosol concentration with the addition of ventilation in their barrier device (Daniel et al. 2021). Complementing these findings, Abi Karam et al. developed an aerosol barrier mask that successfully limited aerosol particles (Abi Karam et al. 2021). According to Issa et al. their technology reduced aerosol concentration by around 45% to 75%

Table 4. Mean and SD of time-averaged particle count concentrations (#/L) in the simulated HCP breathing zone, and the percent reduction in concentration relative to the control condition (no device), by the number and location of ports "broken" by simulated arms.

Particle size bin[b]	Two ports[a]						
	Particle conc. (#/L)				% reduction		
	Control 1	*H*	*L*	*R*	*H*	*L*	*R*
1	20 100 (14 800)	479 (253)	357 (119)	1100 (344)	97.62% (0.12)	98.22% (0.01)	94.52% (0.02)
2	12 600 (10 100)	154 (153)	113 (69)	589 (216)	98.78% (0.01)	99.10% (0.01)	95.33% (0.01)
3	417 (412)	9 (8)	7 (7)	17 (14)	97.97% (0.01)	98.35% (0.01)	95.89% (0.01)
Total	28 800 (21 900)	579 (346)	432 (147)	1500 (481)	97.99% (0.01)	98.50% (0.00)	94.81% (0.01)

	Four ports						
	Control 1	*H* + *L*	*H* + *R*	*L* + *R*	*H* + *L*	*H* + *R*	*L* + *R*
1	20 100 (10 000)	790 (241)	1,560 (643)	1,180 (644)	96.07% (0.01)	92.22% (0.03)	94.14% (0.03)
2	8,800 (5,260)	352 (147)	758 (227)	600 (410)	96.00% (0.02)	91.39% (0.03)	93.18% (0.05)
3	109 (92)	10 (9)	20 (14)	18 (17)	90.58% (0.08)	81.50% (0.13)	83.66% (0.16)
Total	25 300 (1,340)	1020 (306)	2,050 (717)	1,580 (915)	95.98% (0.01)	91.88% (0.03)	93.76% (0.04)

	Six ports		
	Control 1	*H* + *L* + *R*	*H* + *L* + *R*
1	10 200 (10 200)	592 (109)	94.20% (0.01)
2	4,140 (4,290)	95 (67)	97.70% (0.02)
3	190 (193)	9 (8)	95.44% (0.04)
Total	14 500 (14 700)	696 (143)	95.21% (0.01)

[a]Tests involved "breaking" pairs of ports at the patient's head (*H*), patient's left side (*L*), and/ or patient's right (*R*) side.

(Issa et al. 2021), which was much less than the device tested in this study. Finally, Workman et al. confirmed the efficiency and utility of such devices by reporting no detectable aerosol escape during procedures, as well as excellent patient satisfaction (Workman et al. 2021). All of these studies highlight the value of barrier enclosures in reducing exposure and transmission risk of respiratory pathogens like SARS-CoV-2.

While these results show that the U-COVER design has the potential to reduce aerosol and surface contamination outside the device, this and similar devices need further development and evaluation in healthcare settings to ensure effectiveness and fit with patient care needs. The U-COVER and similar devices may not eliminate the need for other controls, including PPE, but they can offer an additional barrier of protection. Additionally, although there are no metrics from authoritative organizations for how such devices should perform, a benchmark could be exposure reduction similar to an N95 filtering facepiece respirator, which has an assigned protection factor of 10, equal to a 90% reduction in the aerosol concentration in the facepiece. The devices tested in this study provide an equal or greater reduction in respirable aerosol concentration at the breathing zone of an HCP, even during simulated use (Table 4).

Future research on these devices should center on the additional testing required to move from efficacy to effectiveness that is how the device works while procedures are being performed with patients in actual patient care settings. Evaluating differences based on patient breathing rate or pulsating exposures from coughing could be future areas of study for such devices. Additional research could also consider the performance of devices like the U-COVER that are portable relative to devices that are more permanently installed and do not require direct interaction by the HCP. The National Institute for Occupational Safety and Health Headboard is an example of one such engineering control, which provides local exhaust ventilation at the head of the bed without covering the patient's body (CDC 2020). The U-COVER and similar devices, however, have the advantage of portability and ease of set up, enabling use in emergencies, facilities with limited space and infrastructure, or for patient transport.

Table 5. Blank corrected mean and SD fluorescein mass concentration (ng/in^2) and the percent reduction in concentration relative to the control condition (no device), by the number and location of ports "broken" by simulated arms.

Sampling location[1]	Control 2	Two ports[2]			Four ports			Six ports
		H	*L*	*R*	*H + L*	*H + R*	*L + R*	*H + L + R*
		Mean (SD) fluorescein concentration (ng/in^2)						
A1	901 (116)	1.10 (0.30)	0.83 (0.13)	0.26 (0.10)	1.41 (0.06)	1.67 (0.11)	0.31 (0.26)	1.37 (0.16)
A2	1,160 (155)	1.10 (0.61)	0.41 (0.18)	0.69 (0.09)	1.40 (0.07)	1.93 (0.44)	0.28 (0.20)	1.18 (0.10)
B1	622 (49.7)	0.54 (0.33)	1.15 (0.09)	0.24 (0.05)	1.19 (0.12)	0.51 (0.12)	1.40 (0.06)	1.10 (0.26)
B2	1,640 (199)	0.90 (0.35)	0.51 (0.15)	1.64 (0.21)	0.58 (0.15)	1.39 (0.13)	1.60 (0.04)	1.16 (0.24)
C1	584 (54.7)	0.39 (0.18)	1.15 (0.74)	0.53 (0.13)	1.25 (0.07)	0.60 (0.05)	1.18 (0.10)	1.05 (0.10)
C2	1,060 (145)	0.27 (0.19)	0.13 (0.05)	1.33 (0.08)	0.19 (0.05)	1.17 (0.19)	1.58 (0.17)	0.88 (0.24)
D1	621 (49.0)	0.08 (0.15)	0.05 (0.04)	0.12 (0.02)	0.25 (0.06)	0.23 (0.06)	0.29 (0.13)	0.22 (0.19)
D2	776 (62.1)	0.01 (0.63)	0 (0.02)	0.22 (0.15)	0 (0.03)	0.13 (0.02)	0.11 (0.06)	0.17 (0.02)
		Mean (SD) Percent (%) Reduction						
		99.95% (0.44)	99.94% (0.47)	99.94% (0.57)	99.91% (0.60)	99.91% (0.68)	99.91% (0.65)	99.91% (0.45)

[a]*A*1: left, patient head; *A*2: right, patient head; *B*1: left, patient shoulder; *B*2: right, patient shoulder; *C*1: left, patient torso; *C*2: right, patient torso, *D*1: left, patient waist; *D*2: right, patient waist.
[b]Tests involved "breaking" pairs of ports at the patient's head (*H*), patient's left side (*L*), and/ or patient's right (*R*) side.

Limitations

Although a specialized mannequin task trainer with many anatomical features was used for this study, this is not representative of the large variability in human body sizes or anthropometric measurements within the population. This could affect the interface of the device with the patient and therefore potentially affect aerosol containment. In this study, we used aerosolized salt particles and fluorescein as surrogates of patient-generated aerosols. The size, emission pattern, and velocity of these particles may not mimic emission from all patients in a scenario, nor cover the entire range of inhalable aerosols, which could be up to 100 µm in aerodynamic diameter. This is an area for future work, but by focusing on respirable aerosols, which are the ones most likely to be able to be transported outside the device via airflows, the study sought to test the device with the aerosols most difficult to contain.

Further limitations include how the device was operated during this study. The ventilation system for the D_{1A} and D_{1B} designs was set to a fixed air flow rate of 2.12 m^3/min (the highest setting), while the D_2 design had a ventilation system that was fixed to 1.81 m^3/min. The results made it clear that the use of the ventilation system is critical for optimal performance, but future work should explore the device performance at lower airflow rates. Using low airflow rates can reduce noise levels, reduce the device weight, and lower device energy requirements. The device testing was also conducted in a laboratory setting and not in its intended use environments, such as during patient transport or in a healthcare setting. The differences in air movement characteristics in such varied locations could potentially influence the device performance. Similarly, the focus of the evaluation was on a patient in the horizontal position, and we did not test any inclined positions. Because the device is placed only over the upper body of the patient, it would be anticipated that the device would remain in place with a similar function for an inclined position as well.

Conclusions

The U-COVER device remains under development, but early design iterations tested in this study have demonstrated excellent performance in the capture of respirable aerosols, demonstrating that this and similar ventilated aerosol containment devices have the potential to reduce HCP exposure to respiratory pathogens through multiple exposure routes. However, containment efficiency is reliant on several factors, especially active ventilation from the device. The D_2 design performed the best overall, including high containment efficiency even during simulated usage tests. The next steps should include performance evaluation using lower exhaust ventilation airflow rates, and dynamic use during simulated or actual patient care activities (e.g. intubation). Engineering controls like the U-COVER device provide an opportunity to enhance the protection of HCP from occupationally acquired respiratory infections when used in combination with other control strategies.

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Supplementary data

Supplementary data are available at *Annals of Work Exposures and Health* online.

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Conflict of interest statement

None declared.

Data availability

The data underlying this article are available in the HIVE research data repository at the University of Utah, at https://doi.org/10.7278/S50d-ty62-keqa.

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