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Authors

Fidler, Richard L

Niedek, Christopher R

Teng, Justin J

et al.

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Aerosol Retention Characteristics of Barrier Devices

Richard L. Fidler, Ph.D., M.B.A., C.R.N.A., N.P.,
Christopher R. Niedek, B.S., Justin J. Teng, M.D.,
Mary E. Sturgeon, D.M.D., Qi Zhang, Ph.D.,
David L. Robinowitz, M.D., M.H.S., M.S.,
Jan Hirsch, Ph.D., M.D.

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EDITOR'S PERSPECTIVE

What We Already Know about This Topic

- Multiple intubation barrier devices have been developed to block droplet exposure. However, aerosol protection with these devices is either not known or not consistently studied.

What This Article Tells Us That Is New

- In studies evaluating multiple systems, only closed devices, semiclosed devices, and aerosol boxes reduced exposure to aerosol particle counts. As a result, barrier devices must be used in conjunction with body-worn personal protective equipment.

ABSTRACT

Background: Disease severity in coronavirus disease 2019 (COVID-19) may be associated with inoculation dose. This has triggered interest in intubation barrier devices to block droplet exposure; however, aerosol protection with these devices is not known. This study hypothesized that barrier devices reduce aerosol outside of the barrier.

Methods: Aerosol containment in closed, semiclosed, semiopen, and open barrier devices was investigated: (1) "glove box" sealed with gloves and caudal drape, (2) "drape tent" with a drape placed over a frame, (3) "slit box" with armholes and caudal end covered by vinyl slit diaphragms, (4) original "aerosol box," (5) collapsible "interlocking box," (6) "simple drape" over the patient, and (7) "no barrier." Containment was investigated by (1) vapor instillation at manikin's right arm with video-assisted visual evaluation and (2) submicrometer ammonium sulfate aerosol particles ejected through the manikin's mouth with ventilation and coughs. Samples were taken from standardized locations inside and around the barriers using a particle counter and a mass spectrometer. Aerosol evacuation from the devices was measured using standard hospital suction, a surgical smoke evacuator, and a Shop-Vac.

Results: Vapor experiments demonstrated leakage *via* arm holes and edges. Only closed and semiclosed devices and the aerosol box reduced aerosol particle counts (median [25th, 75th percentile]) at the operator's mouth compared to no barrier (combined median 29 [−11, 56], n = 5 *vs.* 157 [151, 166], n = 5). The other barrier devices provided less reduction in particle counts (133 [128, 137], n = 5). Aerosol evacuation to baseline required 15 min with standard suction and the Shop-Vac and 5 min with a smoke evacuator.

Conclusions: Barrier devices may reduce exposure to droplets and aerosol. With meticulous tucking, the glove box and drape tent can retain aerosol during airway management. Devices that are not fully enclosed may direct aerosol toward the laryngoscopist. Aerosol evacuation reduces aerosol content inside fully enclosed devices. Barrier devices must be used in conjunction with body-worn personal protective equipment.

(ANESTHESIOLOGY 2021; 134:61–71)

In the coronavirus disease 2019 (COVID-19) pandemic, healthcare workers are facing a substantial personal risk of acquiring SARS–CoV-2.[1] In particular, data that severity of illness may be related to infectious viral dose[2] and shortages of personal protective equipment triggered interest in using barrier devices during certain aerosol generating procedures, such as intubation.[3–8] These devices (fig. 1) include the "aerosol box,"[8] "drape tent,"[4] and "simple drape."[5] The devices are meant to be used in addition to other forms of body-worn person protective equipment.

Exhaled viral particles are found in two different forms: droplets and aerosols. Depending on size, droplets (approximately 20 μm and above) generally follow gravity and fall to the ground within seconds.[9] However, even large droplets (over 100 μm) can travel up to 6 m with sneezing, up to 2 m with coughing, and less than 1 m with normal breathing.[9] Aerosols generally consist of small droplets or droplet nuclei of 1 to 10 μm or less, which stay suspended in the air almost indefinitely and are mainly subject to the ambient air velocity field.[9] Canelli *et al.*[3] demonstrated that the original "aerosol box" reduced exposure to droplet contamination. Although droplets contain more virus particles and are an established means of virus transmission,[9] there is also concern regarding transmission *via* aerosol.[9–12] Studies have detected influenza virus RNA in human exhaled breath even during tidal breathing.[9,12] More recent data support a role for transmission of SARS–CoV-2 by aerosol.[13,14] This research focused on the long-range airborne route.[9]

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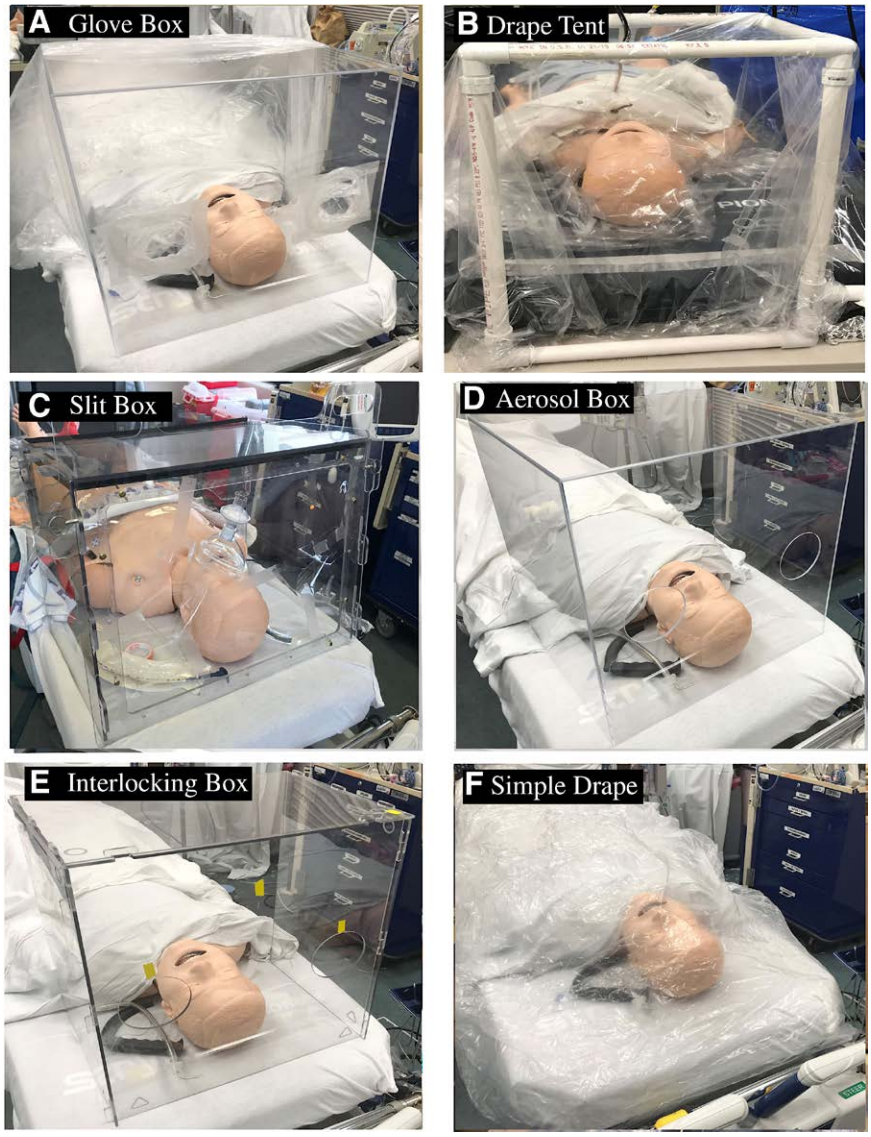

Fig. 1. Overview of barrier devices. (*A*) Glove box. (*B*) Drape tent. (*C*) Slit box. (*D*) Aerosol box. (*E*) Interlocking box. (*F*) Simple drape.

Although the original barrier device design is called an aerosol box, only very limited data regarding the ability of these devices to protect the user from aerosol are currently available.[4] This study aims to qualitatively describe aerosol behavior using a vapor generator, and quantitatively describe aerosol behavior using a condensation particle counter and aerosol mass spectrometer with nine open, semiopen, semienclosed, and closed barrier devices. The main hypothesis is that all barrier devices lead to a reduction in aerosol content outside of the device. The secondary aims of this study are to characterize longer-term (min) aerosol containment that can be achieved by barrier devices and explore strategies for safe aerosol management with different barrier device designs.

Materials and Methods

The research goals were to qualitatively evaluate the aerosol containment characteristics of barrier devices using a vapor generator, and quantitatively describe barrier device aerosol containment using a condensation particle counter and aerosol mass spectrometry. The study was evaluated by the institutional review board of our institution, which declined the requested review and advised that no institutional review board approval was necessary in the absence of human subjects.

Devices

The following devices were evaluated: (1) glove box, an edge-sealed box with long gloves sealing the armholes and

a cover extending caudally over the patient; (2) drape tent, a plastic drape placed over a frame at the patient's head with airway management through the drape; (3) slit box, armhole openings covered by a vinyl sheet with a slit diaphragms cut for arm openings, and a vinyl sheet occluding the caudal side; (4) the original aerosol box, an edge-sealed box with open arm holes and open caudal side, sometimes combined with a caudal drape; (5) interlocking box, a collapsible polycarbonate box to facilitate disinfection and transport with interlocking tabs and unsealed edges, open armholes and open caudal end; and (6) simple drape, a clear plastic drape placed directly over the patient with the laryngoscopist's hands working from beneath the drape. We grouped devices as "closed" (glove box, drape tent), "semiclosed" (slit box), "semiopen" (aerosol box, interlocking box, simple drape), and "open" (no barrier).

Setup for Experimental Series

A Laerdal (Norway) ALS manikin was placed on a 10-cm-thick standard hospital gurney mattress. The gurney height was standardized at 73 cm (28.7 inch). Each barrier device was placed over the manikin on a gurney at a specified location 2.5 cm above the top of the manikin head.

Visualization of Vapor Leakage

A vapor generator (Chauvet Inc., USA: DJ Hurricane 700 and DJ Fog Fluid FJU) was used to generate visible vapor. Within each barrier device, vapor was instilled for 5 s from a standardized position at the right arm. Subsequently, the opening was closed, and distribution and leakage of vapor were recorded by video captured on an iPhone 11 Pro Max at 1,080 dpi at 60 frames/s and analyzed by visual inspection. For the vapor experiments, the air exchange was turned off in the room where the experiments took place.

Aerosol Leakage

These experiments were done in a temperature and humidity-controlled laboratory environment in the Department of Environmental Toxicology at University of California, Davis (fig. 1). Ventilation was provided by the ventilation system in the ceiling of the test room. After erecting barriers to block air flow from the mass spectrometer's cooling fans, investigators could not detect airflow in the experimental environment.

Ammonium sulfate was chosen because of low background amounts in our experimental site and its established use in aerosol research.[15–17] The aerosol was directly measured, both for ammonium sulfate mass concentration and for particle number.[18]

Ammonium sulfate can be quantitatively sampled and measured by mass spectrometry.[15,16] Submicrometer aerosols were generated using a collision atomizer and a diffusion dryer from a (50 ppm $(NH_4)_2SO_4$) solution. A constant flow of filtered air was generated at 3 l/min and 30 psi pressure using a laboratory air pump (GAST Manufacturing, USA; model DOA-P704-AA). Respiratory movement was simulated with a 500-ml Jackson–Rees system, with the aerosol line connected to the oxygen port and the expiratory valve closed. Preliminary experiments with different sizes of Jackson–Rees systems did not show a difference in aerosol detection at the manikin mouth, open arm holes, and operator's mouth with different tidal volumes (data not shown). The aerosol mixture was routed *via* low absorption tubing through the opening for cricothyrotomy training to a standardized posterior oropharynx position inside the manikin's mouth. The aerosol mixture could flow freely inside the barrier device, with the average particle size 0.168 μm (25th to 75th percentile, 63 to 358 nm).

For the experiments, the manikin was placed on a 10-cm-thick thick gurney mattress that was placed on a 73-cm-high high table. The aerosol content was measured at the following standardized positions: (1) manikin mouth, 2.5 cm above the manikin's mouth; (2) caudal Superior, at the caudal end of the box above the manikin's sternum (38 cm from manikin mouth); (3) operator's mouth, at the position of a 175-cm-tall operator's mouth above the cranial side of the box (47.6 cm from manikin mouth); (4) left Arm hole, at the top of the left arm hole (25 cm from manikin mouth; data for the right arm hole were obtained and paralleled the left arm hole; (5) operator's chest (operator was 175 cm tall), 10 cm above the upper end of both arm holes outside of the box (29.5 cm from manikin mouth). For the simple drape experiments, measurements were taken at positions 1 and 3a (20 cm above the manikin's forehead outside the barrier and 21 cm from manikin mouth), simulating the position of the operator's head when doing a direct laryngoscopy. For comparison, position 3 measurements (GlideScope position) were also obtained.

For cough experiments, measurements were repeated with an aerosol box, and measurements were obtained at positions 1, 3, and 4. Without a barrier device, the measurements were performed at positions 1 and 3.

Aerosols were generated with an atomizer using air flow from a constant suction pump at 200 ml/min. The air was routed toward a TSI 3772 condensation particle counter (TSI Inc., USA; model 3772) that was operated at a 1:10 dilution ratio to measure aerosol number concentration in the air with 1-s averaging. Simultaneously, measurements of ammonium sulfate mass concentration were performed on an Aerodyne soot-particle high-resolution time-of-flight aerosol mass spectrometer (Aerodyne Research, USA)[17] using the "Fast MS" mode with 1-s averaging.[18] Particle size distributions were determined by the aerosol mass spectrometer using the standard "GenAlt" mode with 2-min averaging. Measurements were performed for 5 min in each position to minimize artifacts from source switching. Cough and drape opening experiments were done for five repetitions.

Cough Experiments

Based on work by Gupta *et al.*,[19] a cough model was developed using the Laerdal simulation manikin. Cough was defined as a rapid (less than 1 s) expulsion of up to 1,600 ml air at a peak expiratory flow of approximately 510 l/min, measured at the mouth. This was accomplished by connecting a 1,600-ml self-inflating bag resuscitator (Portex 1st Response adult resuscitator, Smiths Medical, USA) *via* 18 inches of 22-mm tubing to the tracheal bifurcation of the manikin. The other main bronchus, the esophagus, and the nose of the manikin were occluded.

A peak flow meter (TruZone peak flow meter, Monaghan Medical Corporation, USA) was inserted in the manikin's mouth. The manikin's mouth was sealed with tape around the peak flow meter, resulting in a 1.25-inch-diameter opening. In preliminary experiments it was established that rapid full deflation of the resuscitator with the fist of one operator from a standardized height at full force would lead to a consistently reproducible peak flow of 500 l/min in less than 1 s. The oxygen inlet of the resuscitator bag was connected to the output of the aerosol generator, filling the reservoir bag. Before the experiment, the bag and reservoir were filled with aerosol.

Evacuation Experiments

Vapor evacuation testing was performed with hospital wall suction on maximum continuous setting (240 mmHg), connected to standard suction tubing without a suction catheter attached. The following suction devices were evaluated using a Stryker (USA) Neptune waste management and smoke evacuator system: standard hospital suction (240 mmHg, connected to standard suction tubing without a suction catheter); high suction (500 mmHg, connected to standard suction tubing without a suction catheter); and smoke evacuator with a 22-mm hose at maximum setting. In addition, a 12-gallon, 4.5-horsepower, 175-cubic feet/min, 60-inch water-sealed pressure (112 mmHg) Shop-Vac (Shop-Vac QuietPlus, model 59812, Shop-Vac, USA) was tested using an inline polypropylene filter (Portex 002863, Smiths Medical) placed on the vacuum hose. Air flow was visualized by using a light dry paper wipe as an indicator attached to the inside ceiling of the barrier device using a 1-inch piece of tape (34155 Kimtech Wipes, 4.4 × 8.8 inches, Kimberly Clark, USA).

Data Analyses

The data were collected from March 28, 2020, to May 4, 2020, in the unused (because of COVID-19 restrictions) recovery room at Marin General Hospital and in Dr. Zhang's laboratory at the Department of Environmental Toxicology at University of California, Davis. All authors and only the authors participated in data collection. For vapor experiments, a dedicated team of raters was selected (R.L.F., D.L.R., and J.H.). Aerosol experiments were performed by a standardized team of R.L.F., C.R.N., D.L.R., Q.Z., and J.H. with minimal variation in roles. J.J.T. and M.E.S. assisted in experiments, performed literature searches, and participated in study design and manuscript preparation. The barrier devices were grouped into closed (glove box and drape tent), semiclosed (slit box), semiopen (aerosol box, interlocking box, and simple drape), and open (no barrier).

No statistical power calculation was conducted before the study. The sample size was based on our preliminary data with this experimental design. There were no missing data. The data are expressed as medians [25th percentile, 75th percentile], and the maximum particle count measurements are provided. All measurements were performed for 5 min (approximately 40 ventilatory cycles) or five repetitions for cough experiments. Although the aerosol generator and the constant flow air pump constantly filled the reservoir bag, differences in dilution and airflow with the simulated breathing led to oscillations of aerosol counts with the simulated respiratory cycle around the midline. These oscillations created large variability in the data. Microdroplets generated during breathing are reported to originate mainly from the lower airways because of the film rupture mechanism,[9] and fine aerosols have been demonstrated to contain culturable virus particles.[12] Therefore, it was reasoned that the effect observed in our experiment is analogous to a breathing patient, a concentration difference similar to end tidal carbon dioxide in capnography. Although the operator is exposed to the whole respiratory cycle, we further reasoned that the maximum aerosol content is the parameter of interest when using aerosol concentration and particle counts as a proxy for viral content.

Therefore, after visual interpretation of the raw particle count curves, the top 15% quantiles of each sampling position were selected for comparison. Quantiles were calculated using the Harrell–Davis estimator.[20,21] Statistical comparisons were done between the median of the top 15% quantile particle count data points for each minute of experiments (n = 5) or each cough experiment (n = 5) and the baseline. The data were normalized to the average baseline particle count value for the day by subtraction. IBM SPSS Statistics Subscription (catalog number 11-2018; IBM, USA) was used for statistical comparisons. *P* values were calculated with a two-tailed Mann–Whitney U test for independent samples. A total of 38 statistical comparisons were performed.

Significance levels were corrected for multiple comparisons using the false discovery rate.[22] A false discovery rate of 0.05 (the fraction of positive tests that are false positives) was specified. *P* values above the false discovery rate threshold are reported as such. In all cases, the uncorrected Mann–Whitney *P* value is provided. Maximum aerosol counts at all locations are provided to describe consistency of aerosol containment with the devices.

Results

Vapor Experiments

For the semiclosed and closed devices, preliminary experiments were performed to optimize barrier properties. It was determined that turning the gurney mattress 180° head to toe greatly decreased visible leakage from under the glove box and slit box because of the tapering of the mattress on both corners at the head end. Meticulous tucking of drapes under the mattress' edge and putting a towel across the patient's chest further reduced visible vapor leakage and decreased the volume of vapor in the containment device. Substantial amounts of vapor leaked when tubing or cables were inadvertently routed below the box instead of routing through the caudal end of the box. In addition, if the box was lifted from the mattress during airway manipulation, vapor was noted to escape from under the fully sealed glove box. For the drape tent, the use of a larger drape allowed enough "slack" to greatly reduce the likelihood of drape dislodgement during airway management.

Even under optimized conditions, the vapor experiments demonstrated visible leakage in all semiopen devices. Vapor escaped through the armholes and traveled toward the face and chest of the operator. This was particularly pronounced if the caudal end of the box was closed with a plastic drape while the arm holes or slits were left open (fig. 2). In devices without sealed edges (interlocking box and slit box), vapor escaped along the edges (fig. 3).

The simple drape maintained a good seal when the drape was left in place and snugly tucked. However, once laryngoscopy was initiated and the drape was lifted, large amounts of vapor escaped and were directed toward the laryngoscopist (fig. 4). Manipulation through the drape while keeping the drape tucked in was possible with the drape tent but required a very large and transparent drape.

Aerosol Experiments

Numerical values and results of statistical comparison testing for all aerosol measurements are provided in table 1.

Glove Box. Particle counts at all measurement locations were at least 70% lower than no barrier. With the exception of the operator chest location, counts were statistically significantly elevated compared to baseline at all locations outside the box (table 1).

Drape Tent. With the drape tucked under the mattress, particle counts were at least 50% lower at all measurement locations than without a barrier, albeit statistically significantly elevated from baseline and higher than the glove box (table 1).

Slit Box. The vinyl sheets at the caudal end and the arm holes of the slit box resulted in 4-fold higher counts at the caudal superior and 32-fold higher at the arm hole compared to no barrier (table 1). Counts at the operator's mouth and operator's chest were at or below baseline, but maximum counts indicated less uniformity in retaining aerosol than with fully enclosed devices.

Aerosol Box. Compared to no barrier, aerosol counts at the operator's mouth were reduced 20-fold, and there was a 3-fold decrease at the operator's chest. Containment at these locations was more consistent than with the slit box. There was a 25-fold higher particle count at the arm hole compared to baseline. (table 1). Adding a drape to the aerosol box but leaving the arm holes open resulted in no noticeable particle counts at the caudal superior location and unchanged particle counts at the operator's mouth. Higher particle counts were registered at the arm hole (74-fold) and a 5-fold increase at the operator's chest.

Interlocking Box. At the operator's mouth and chest, there were similar aerosol sampling patterns as with no barrier (table 1), whereas there was a 3-fold higher particle count at the arm hole. Slightly elevated counts compared to no

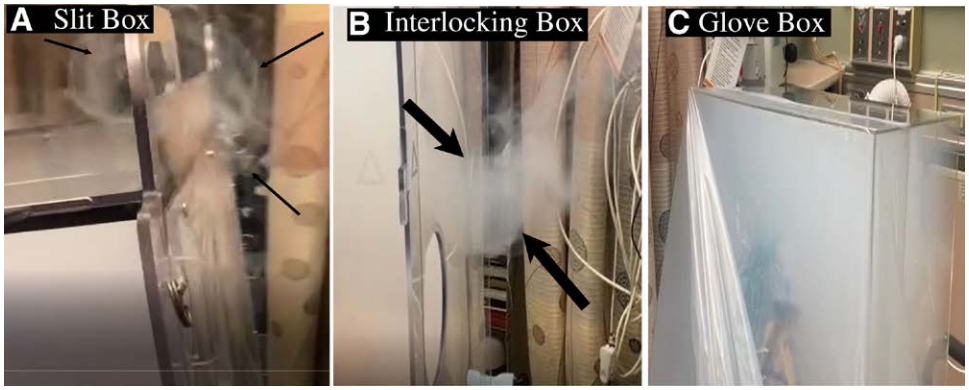

Fig. 2. Differences in vapor egress at the arm holes between barrier devices. *Arrows* show vapor egress. (*A*) Slit box. (*B*) Interlocking box. (*C*) Glove box with no visible vapor egress. The video in the Supplemental Digital Content (http://links.lww.com/ALN/C502) provides additional visualization of vapor egress.

Fig. 3. Vapor egress (*arrows*) from the unsealed edge of the interlocking box. The video in the Supplemental Digital Content (http://links.lww.com/ALN/C502) provides additional visualization of vapor egress.

barrier were found at the caudal superior location and the operator's chest. At the upper edge, where two panels of the box interlock, there was a 3-fold higher particle count compared to no barrier. The much higher counts at the upper edge compared to the slit box were likely due to the rubber gaskets that seal the edges of the slit box system.

Adding a drape to the interlocking box while leaving the arm holes open resulted in lower particle counts at the caudal superior location. Conversely, a 32-fold higher particle count was found at the arm hole, 5-fold higher counts at the operator's chest, and 10-fold higher counts at the upper edge.

Simple Drape. With the simple drape tucked in place, particle counts at the operator's mouth location were slightly lower than baseline and similar to most of the semiopen devices, but a higher maximum count indicated less reliable aerosol retention (table 1). When the drape had to be carefully lifted to intubate the manikin, an increase in aerosol content was found at the operator's mouth in some, but not all of the opening events.

No Barrier Device. Without a barrier device, particle counts at the operator's mouth were elevated compared to most of the barrier devices, especially closed and semiclosed devices and the aerosol box.

Cough Experiments

The data and results of statistical comparisons for the cough experiments are provided in table 2. The simulated coughs led to roughly 20-fold higher particle counts compared to tidal volume breathing while using the aerosol box. Adding a drape to the aerosol box, resulted in more than 15-fold higher aerosol counts at the operator's mouth and the arm hole.

Evacuation Experiments

Aerosol content in a closed box followed a linear decrease when left to normal dispersion and settling. Figure 5 provides graphic visual representation of these experiments. Next, the effect of using a suction device to mitigate the escape of vapor and aerosol was evaluated. Wall suction at 240 mmHg did not lead to a noticeable difference in the quantity of escaping vapor or detection of aerosol in the

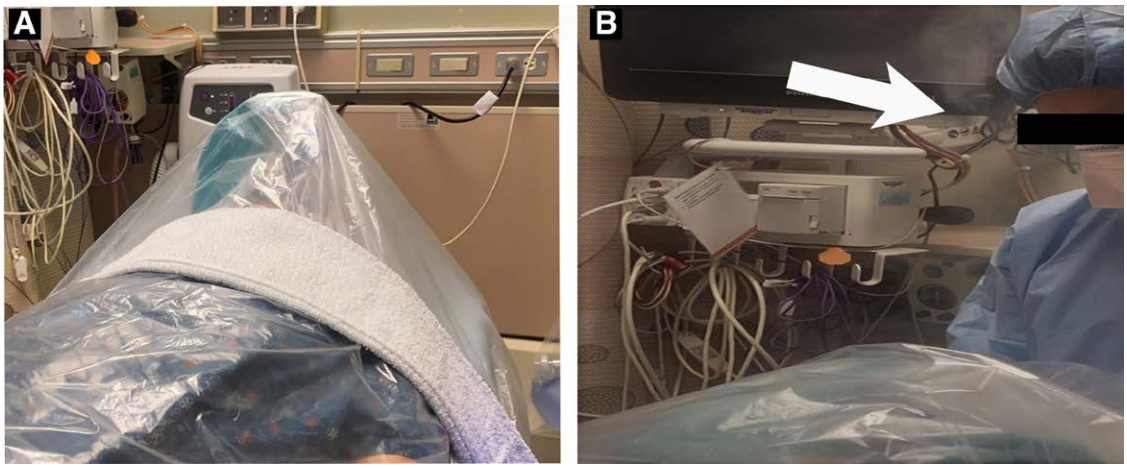

Fig. 4. Simple drape. (*A*) no vapor is visible while the simple drape is in place. (*B*) Vapor is visible at the 175-cm-tall operator's face during airway management. The video in the Supplemental Digital Content (http://links.lww.com/ALN/C502) provides additional visualization of vapor egress.

Table 1. Aerosol Particle Counts Compared to Corrected Baseline

	Manikin Mouth	Caudal Superior	Operator Mouth	Arm Hole	Operator Chest	Box Edge
Closed						
Glove box	41,100 [41,100, 41,200] Max: 41,800 n = 5	19 [6, 27] Max: 50 n = 5 $P = 0.011$	51 [48, 52] Max: 67 n = 5 $P < 0.001$	41 [40, 42] Max: 81 n = 5 $P < 0.001$	–4 [–8, 4] Max: 20 n = 5 $P < 0.711$	n/a
Drape tent	42,000 [41,800, 42,000] Max: 42,700 n = 5	58 [58, 58] Max: 191 n = 5 $P < 0.001$	71 [68, 72] Max: 84 n = 5 $P < 0.001$	n/a	54 [54, 57] Max: 66 n = 5 $P < 0.001$	n/a
Semiclosed						
Slit box	41,600 [41,500, 41,600] Max: 42,200 n = 5	643 [–34, 1,314] Max: 2,529 n = 5 $P = 0.361$	–63 [–71, –27] Max: 500 n = 5 $P = 0.027$	5,180 [3,130, 8,290] Max: 17,600 n = 5 $P < 0.001$	–11 [–55, 21] Max: 919 n = 5 $P = 0.872$	–82 [–96, –53] Max: 140 n = 5 $P < 0.001$
Semiopen						
Aerosol box	37,100 [36,200, 37,900] Max: 40,900 n = 5	86 [74, 274] Max: 2,032 n = 5 $P < 0.001$	7 [4, 13] Max: 23 n = 5 $P < 0.115$	4,000 [3,695, 4,360] Max: 6,095 n = 5 $P < 0.001$	47 [38,78] Max: 255 n = 5 $P < 0.002$	n/a
Aerosol box with drape	40,100 [40,000, 40,400] Max: 41,200 n = 5	–36 [–39, –25] Max: 31 n = 5 $P = 0.001$	12 [5, 20] Max:27 n = 5 $P = 0.084$	11,600 [9,920, 12,800] Max: 23,510 n = 5 $P < 0.001$	847 [720, 1,890] Max: 5,413 n = 5 $P < 0.001$	n/a
Interlocking box	40,300 [40,200, 40,700] Max: 42,200 n = 5	164 [150, 183] Max: 715 n = 5 $P < 0.001$	142 [140, 145] Max: 218 n = 5 $P < 0.001$	454 [187, 617] Max: 2,308 n = 5 $P < 0.001$	174 [170, 206] Max: 969 n = 5 $P < 0.001$	463 [433, 681] Max: 1,747 n = 5 $P = 0.001$
Interlocking box with drape	41,300 [41,100, 41,400] Max: 42,000 n = 43	59 [56, 60] Max: 965 n = 5 $P < 0.001$	129 [29, 135] Max: 143 n = 5 $P < 0.001$	14,800 [12,500, 15,600] Max: 29,300 n = 5 $P < 0.001$	786 [409, 849] Max: 1,926 n = 5 $P < 0.001$	4,247 [2,140, 4,770] Max: 11,200 n = 5 $P < 0.001$
Simple drape, closed	33,200 [32,200, 33,700] Max: 39,400 n = 5	n/a	123 [116, 129] Max: 977 n = 5 $P < 0.001$	n/a	n/a	n/a
Simple drape, opening drapes	n/a	n/a	128 [64, 2,360] Max: 10,010 n = 5 $P < 0.001$	n/a	n/a	n/a
Open						
No barrier	39,400 [38,900, 39,400] Max: 40,700 n = 5	n/a	157 [151, 166] Max: 287 n = 5 $P < 0.001$	n/a	n/a	n/a

Particle counts reported as median [25th, 75th percentile] of the top 85th quantile and were normalized to the average baseline value for each day by subtraction to obtain the corrected baseline. The maximum registered particle count is provided (Max). Significance levels are from the Mann–Whitney U test. Multiple comparison threshold criteria (false discovery rate) were met for all reported ($P < 0.05$).

n/a, not applicable.

semiopen or semienclosed devices. However, 15 min of wall suction at 240 or 500 mmHg or Shop-Vac with filter completely evacuated visible smoke and detectable aerosol from the interior of the fully closed barrier devices. Use of the smoke evacuator was clearly more efficient and reduced this clearance time to 5 min. The smoke evacuator, and to a lesser degree the Shop-Vac, produced detectable air flow away from the operator if the caudal side of the barrier

Table 2. Aerosol Particle Counts in Cough Experiments Compared to Corrected Baseline

	Manikin Mouth	Operator Mouth	Arm Hole
Aerosol box	4,270 [2,300, 4,360] Max: 39,900 n = 5	240 [229, 249] Max: 345 n = 5 $P < 0.001$	736 [722, 1,000] Max: 1,493 n = 5 $P < 0.001$
Aerosol box with drape		2,160 [1,690, 2,480] Max: 4,060 n = 5 $P < 0.001$	2,250 [1,980, 3,390] Max: 7,200 n = 5 $P < 0.001$
No barrier		219 [202, 480] Max: 1,523 n = 5 $P < 0.001$	n/a

Particle counts reported as median [25th, 75th percentile] of the top 85th quantile and were normalized to the average baseline value for each day by subtraction to obtain the corrected baseline. The maximum registered particle count is provided (Max). Significance levels are from the Mann–Whitney U test. Multiple comparison threshold criteria (False Discovery Rate) met for all reported ($P < 0.05$).

n/a, not applicable.

device was occluded with a drape or vinyl sheet. This was also true for devices with slits and arm holes.

Discussion

These experiments demonstrate that fully enclosed barrier devices cause a reduction of vapor and aerosol detection in the area of the operator. If no barrier device is used, aerosol content is 1 order of magnitude higher than using a fully enclosed device. Semiclosed barriers caused vapor and aerosol leakage through the arm apertures and were found to increase aerosol at the operator's face. Furthermore, the aerosol spread toward the operator was increased if the caudal side of the semiclosed barrier was closed. Regular hospital suction inside the box was insufficient to redirect airflow away from the operator, whereas a Shop-Vac or a smoke evacuator resulted in detectable air flow away from the operator. Although semiopen devices reduced aerosol content in the operator's area, this reduction was generally less consistent than the semiclosed devices, and aerosol was concentrated at the arm holes. Use of a simple drape resulted in an inconsistent reduction of aerosol compared to no barrier. In particular, vapor and aerosol escaped once the simple drape was lifted for airway manipulation.

Aerosol exposure is clinically relevant, because both aerosol and droplet provide exposure risk for COVID-19,[13,14] and data from influenza suggest that viruses can produce disease with as few as 1 to 100 infectious units.[21–23] These results provide evidence that barrier devices may provide some protection against directional air flow, particularly with patient coughing. Importantly, these devices permit the egress of aerosol toward the operator. In particular, vapor escape and higher particle counts were observed at the arm holes and the operator's chest. This study did not evaluate the impact of aerosol spread within the operator's body plume[9] or the benefits of body-worn personal protective equipment.

Higher particle counts on the operator side were further enhanced when the caudal side of the device was occluded. When a caudal drape is used, aerosol will be redirected toward the operator. With not fully enclosed devices, leaving the caudal side open may be considered, so the arm openings are not the only escape route for aerosol. Caudal displacement of contaminated air with an open caudal side is still possible. Potentially a caudal jet effect would be smaller than the effect at the arm holes due to the larger opening.

Without a caudal drape, airflow in the procedure room may encourage aerosol movement out of the barrier device. These results demonstrate that only meticulously placed fully enclosed devices such as glove box or drape tent consistently reduced aerosol close to baseline values outside the barrier device, containing the aerosol inside the barrier. This finding adds important additional information to another study that compared the use of an aerosol box with a drape and a sealed box with coughing.[24]

Based on these data, consideration should be given to narrowing the definition of barrier devices. Because of inconsistent aerosol retention, the original aerosol box is more appropriately called a "droplet box."[3,4] The term "aerosol box" should be reserved for fully enclosed devices. Although previous studies[4] and these data show retention of most aerosols with fully enclosed devices, aerosol counts were statistically significantly elevated above baseline outside of all categories of devices, although it is not known whether this is clinically significant. Even with fully closed devices, aerosol counts outside the barrier device were reduced but still statistically significantly elevated above baseline, highlighting the importance of personal protective equipment. Coughing, sneezing, poor mask fit, and high-flow nasal cannula oxygen lead to higher amounts of aerosol at the intubator's face.[10,19]

This study demonstrates that fully enclosed barrier devices can achieve aerosol containment creating the predicament of aerosol disposal. Drape removal experiments show that a concentrated number of aerosolized particles can be released into the environment with barrier removal if there is no effective evacuation of aerosol from the device. This contained aerosol situation presents an exposure risk to providers if the device needs to be removed rapidly for an airway emergency. Rapid barrier removal may be a necessity in some cases, because recent data demonstrates prolonged intubation times and higher cognitive load for the operator when using a barrier device.[25] If a fully enclosed aerosol barrier device is being used, aerosol evacuation before removal is necessary to minimize aerosol exposure. Based on these experiments (fig. 5), 5 min of suction with a

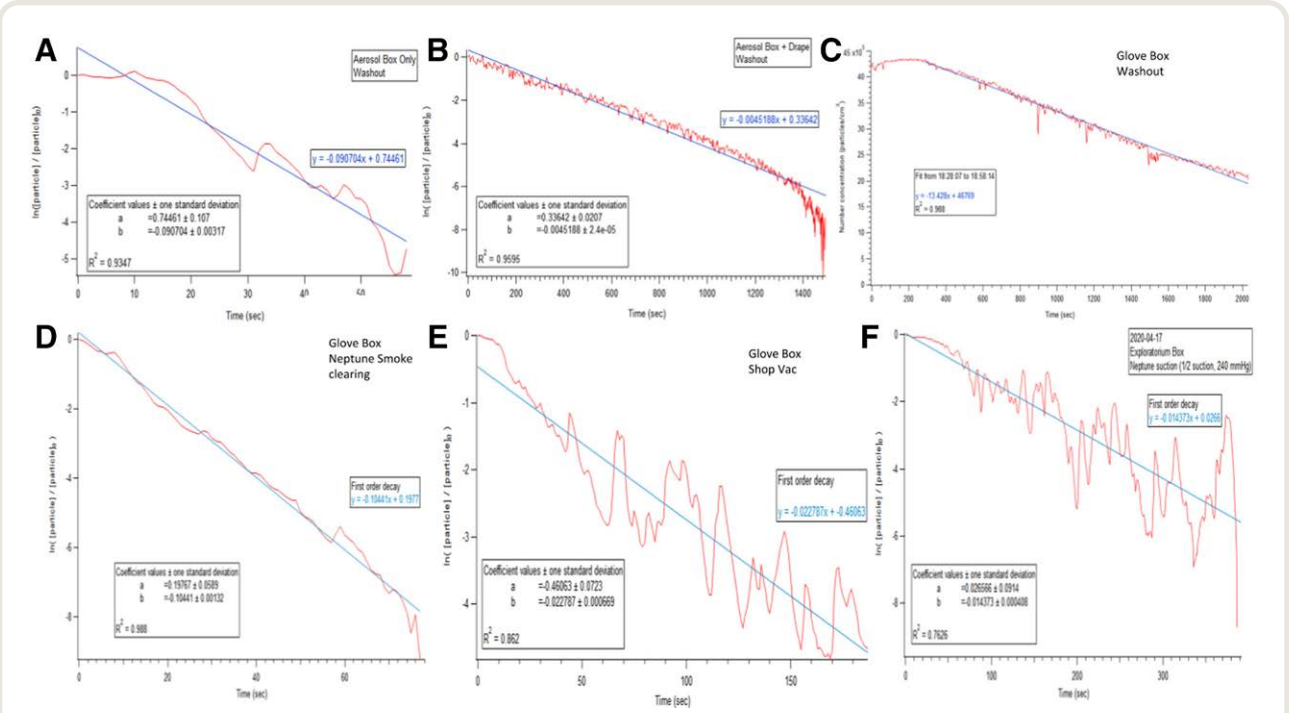

Fig. 5. Smoke evacuation patterns. (*A–C*) Spontaneous washout follows a linear pattern. (*D–F*) Effect of different evacuation methods.

smoke evacuator or 15 min with a 240- or 500-mmHg hospital suction is enough time to bring aerosol content back to baseline inside a fully enclosed barrier device.

Smoke evacuators can provide vacuum and airflow to remove aerosol content from the closed barrier device in under 5 min; however, smoke evacuators are typically operating room equipment and not readily available elsewhere. The Shop-Vac with a viral filter was evaluated for limited resource situations, but the Shop-Vac creates loud noise in the procedure room. Only the smoke evacuator and Shop-Vac, but not regular hospital suction, created air flow away from the operator when used with a semienclosed device. With all suction devices, disposal of contaminated equipment and filtering of expelled air needs special attention.

Additional research on contamination risk in teardown and disinfection is necessary. Removal, disposal, and cleaning of contaminated materials is a consideration for the barrier devices, and each barrier device has advantages. The interlocking box has been developed with cleaning in mind. This study did not evaluate this aspect, and further research is needed to determine the lowest risk of provider exposure in the cleanup phase. Although some of these devices provide flat, easy-to-clean surfaces and minimize the use of drapes, in others the disposal of contaminated materials requires special training (*e.g.*, carefully removing drapes and gloves with the contaminated side inwards).[14] Further investigation of this relationship is complicated by variability in personal protective equipment.[14] In addition, a recent study reported that use of barrier devices prolongs intubation times,[25] increasing exposure time.

There are several limitations to this study. First, the fidelity of the vapor model representing viral aerosol cannot be determined. The polyfunctional alcohol droplets in this type of vapor may possibly travel differently than aerosols from human breath. However, it does appear that the qualitative vapor test results are aligned with the quantitative results from the particle counter and aerosol mass spectrometry experiments. Generalizability to operating rooms is limited because these experiments were not carried out in a laminar air flow environment. For the aerosol tests, we utilized an ammonium sulfate model that is frequently used in aerosol research.[16,17] Although the particle size of this model is known and similar to the widest traveling particles in air exhaled from humans, this aerosol is more homogenous than the mixture of droplets in actual human breaths or coughs.[9,24] In addition, it is not known what constitutes a clinically significant infective aerosol exposure for COVID-19. Although an association between infectious dose and severity of disease for COVID-19 has been described,[2] the relative risk of exposure to droplets *versus* aerosols is unclear.

This study can contribute to the risk, benefit, and safety evaluation of all medical equipment before use. Further research needs to address the critical outcome of infection rates in providers using barrier devices *versus* not using barrier devices. The measurements at the operator's face and operator's chest indicate that protection from aerosol is

improved by maintaining an increased distance between the operator's head and patient's mouth. Video laryngoscopy may be a tool to maintain or increase the distance between the intubator's face and the patient's airway, but this will ultimately be limited by the arm length of the intubator.

Conclusions

Intubation boxes or barrier devices may reduce operator exposure to infectious droplets and aerosol. Although it has been shown that barrier devices afford some degree of droplet protection, our results demonstrate wide variation in aerosol containment. The term "aerosol box" should be used with caution. Counterintuitively, some devices directed aerosol toward the operator, especially when the caudal end was occluded. All barrier devices should only be used as an adjunct to standard personal protective equipment.

Further research is needed to determine multiple aspects of the barrier device approaches to mitigating infection risk. The COVID-19 pandemic triggered rapid introduction of new protective barrier devices. Performance standards have been set for personal protective equipment, but this is currently not the case for barrier devices. Healthcare providers need to be fully aware of the incomplete information and limitations for using these devices to avoid a false sense of security.

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Competing Interests

Dr. Robinowitz serves on a volunteer advisory board for the Anesthesia application for the Epic Corporation (Verona, Wisconsin), for which conference fees are waived. The remaining authors declare no competing interests.

Correspondence

Address correspondence to Dr. Fidler: San Francisco Veterans Affairs Healthcare System, 4150 Clement Street B6 R201, San Francisco, California 94121. richard.fidler@va.gov.

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