

Barrier Devices, Intubation, and Aerosol Mitigation Strategies: Personal Protective Equipment in the Time of Coronavirus Disease 2019

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BACKGROUND: Numerous barrier devices have recently been developed and rapidly deployed worldwide in an effort to protect health care workers (HCWs) from exposure to coronavirus disease 2019 (COVID-19) during high-risk procedures. However, only a few studies have examined their impact on the dispersion of droplets and aerosols, which are both thought to be significant contributors to the spread of COVID-19.

METHODS: Two commonly used barrier devices, an intubation box and a clear plastic intubation sheet, were evaluated using a physiologically accurate cough simulator. Aerosols were modeled using a commercially available fog machine, and droplets were modeled with fluorescein dye. Both particles were propelled by the cough simulator in a simulated intubation environment. Data were captured by high-speed flash photography, and aerosol and droplet dispersion were assessed qualitatively with and without a barrier in place.

RESULTS: Droplet contamination after a simulated cough was seemingly contained by both barrier devices. Simulated aerosol escaped the barriers and flowed toward the head of the bed. During barrier removal, simulated aerosol trapped underneath was released and propelled toward the HCW at the head of the bed. Usage of the intubation sheet concentrated droplets onto a smaller area. If no barrier was used, positioning the patient in slight reverse Trendelenburg directed aerosols away from the HCW located at the head of the bed.

CONCLUSIONS: Our observations imply that intubation boxes and sheets may reduce HCW exposure to droplets, but they both may merely redirect aerosolized particles, potentially resulting in increased exposure to aerosols in certain circumstances. Aerosols may remain within the barrier device after a cough, and manipulation of the box may release them. Patients should be positioned to facilitate intubation, but slight reverse Trendelenburg may direct infectious aerosols away from the HCW. Novel barrier devices should be used with caution, and further validation studies are necessary. (Anesth Analg XXX;XXX:00–00)

KEY POINTS

- **Question:** Are intubation barrier devices effective at reducing health care worker exposure to infectious droplets or aerosols during high-risk procedures, such as intubation or extubation?
- **Findings:** Intubation boxes and sheets may contain droplets during simulated coughs, but some aerosols might be redirected toward the intubator or an assistant next to the patient, and some aerosol may remain trapped underneath the barrier device.
- **Meaning:** Patient positioning may have a significant impact on the direction of aerosol and droplet spread.

GLOSSARY

CDC = Centers for Disease Control and Prevention; **COVID-19** = coronavirus disease 2019; **HCW** = health care worker; **MAD** = mucosal atomization device; **PAPR** = powered air purifying respirator; **PPE** = personal protective equipment; **SARS-CoV-2** = severe acute respiratory syndrome coronavirus 2; **WHO** = World Health Organization

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The era of coronavirus disease (COVID-19) caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has drastically changed infection control guidelines surrounding the appropriate use of personal protective equipment (PPE).^{1,2} Aerosolizing procedures such as intubation, tracheostomy, and noninvasive ventilation carry a high risk for infection transmission in SARS-CoV-1, and the same can be assumed for SARS-CoV-2.³ There have been conflicting recommendations from national specialty societies, illustrating significant disagreement within the medical community over what should be best practice in routine and high-risk patient encounters.^{1,4} Studies have shown that recommendations outlined by the Centers for Disease Control and Prevention (CDC) and the World Health Organization (WHO) may be inadequate for intubation.^{5,6} Finally, there is an emerging body of literature suggesting that aerosols, in addition to droplets, may be a significant contributor to the transmission of viral illnesses such as COVID-19.⁷⁻¹¹ It is now clear that those exposed to aerosol-generating procedures are at considerable risk when followed up during periods of 3 or more weeks.^{12,13}

In response to this pandemic, a global wave of innovation has produced numerous barrier devices, including helmets, face shields, plastic sheets, and intubation boxes.¹⁴⁻¹⁷ Despite widespread clinical use, none of these devices have undergone validation testing in an environment with both droplet (>50 μm) and aerosol (<5 μm) particles.^{5,15-17} Furthermore, there is a paucity of information on how these devices might limit aerosol spread over time. Thus, it is possible that these barrier devices may be harmful by impeding intubation, introducing a nidus for infection, and providing a false sense of security.¹⁸

In this study, we tested 2 commonly used barrier devices, an intubation box and a clear plastic intubation sheet, using a physiologically accurate cough simulator, in an effort to observe their impact on the spread of droplet and aerosol particles. This study is the first to qualitatively evaluate the performance of barrier devices using both droplet and aerosol models.

METHODS

Development of a Cough Simulator

A physiologically accurate cough simulator was built to test the barrier devices. Standard parameters for a human cough used to create this simulator included a duration of approximately 0.5–1 second, an average cough flow rate of 0.48–0.90 L/s, a peak expiratory flow rate of 4.75–6.42 L/s, fine particles (“aerosols”) of <5 μm , and coarse particles (“droplets”) >50 μm .¹⁹⁻²²

Our cough simulator was created using a jet ventilator (BE 183-SU, Instrumentation Industries, Inc,

Bethel Park, PA), T-piece connector, and standard respiratory tubing (Figure 1A, B), mounted inside an intubation mannequin placed in sniffing position.²³

Validation of the Cough Simulator

Using a flow analyzer (BC Biomedical PFC-3000, St Charles, MO), we confirmed that the simulator achieved a flow similar to a physiologic cough, 2.6 L/s. Although this is lower than peak expiratory flow rates reported in the literature, it is significantly higher than average cough flow rates. A cough duration of 0.7–0.9 seconds was selected to best approximate a physiologic cough volume of 1.8–2.3 L. In addition, coughs produced by our simulator were similar in geometry and distance to those observed in Schlieren imaging of coughs in human volunteers, and our simulator produced horizontal coughs similar to those observed in other studies.²⁰

Particle Generation Models

For our aerosol model (Figure 1A), a reservoir bag was placed between the T-piece connector and a commercially available fog machine (Chavuet DJ Hurricane 1200, Sunrise, FL), creating a spread of particle sizes between 10 nm and 10 μm , with 2 dominant particle size distributions at 60 nm and 4 μm .²⁴ Fog was drawn into the tubing from the reservoir via the Venturi effect produced by the jet ventilator. The fog starts as an aqueous mixture, which is then heated to its boiling point and expelled from the machine. It then rapidly expands, dissipates, and cools to room temperature over the course of 20–30 seconds. Its high temperature causes it to rise slowly, similar to cigarette smoke. Compared to a human cough, the fog is hotter, causing it to rise further and faster. However, to mitigate this, all images presented were taken no later than 12 seconds after cough initiation. Furthermore, while fog machines have not previously been used in this specific manner, they have been extensively used to study aerodynamics, such as in wind tunnels, and provide an accurate visualization of airflow for the purposes of PPE analysis.

For our droplet model (Figure 1B), a laryngotracheal mucosal atomization device (MAD; MADgic Laryngo-Tracheal Mucosal Atomization Device, Teleflex, Morrisville, NC), creating droplets with sizes 30–100 μm , was used in place of the reservoir bag in the aerosol model.²⁵

Barrier Devices

A plastic intubation box, or “aerosol box,” was constructed according to publicly available specifications using $\frac{1}{8}$ ” thick, clear acrylic plastic and rubber cement.¹⁴ A 1 \times 1 m intubation sheet was constructed from a standard machine cover made of clear plastic.^{15,16}

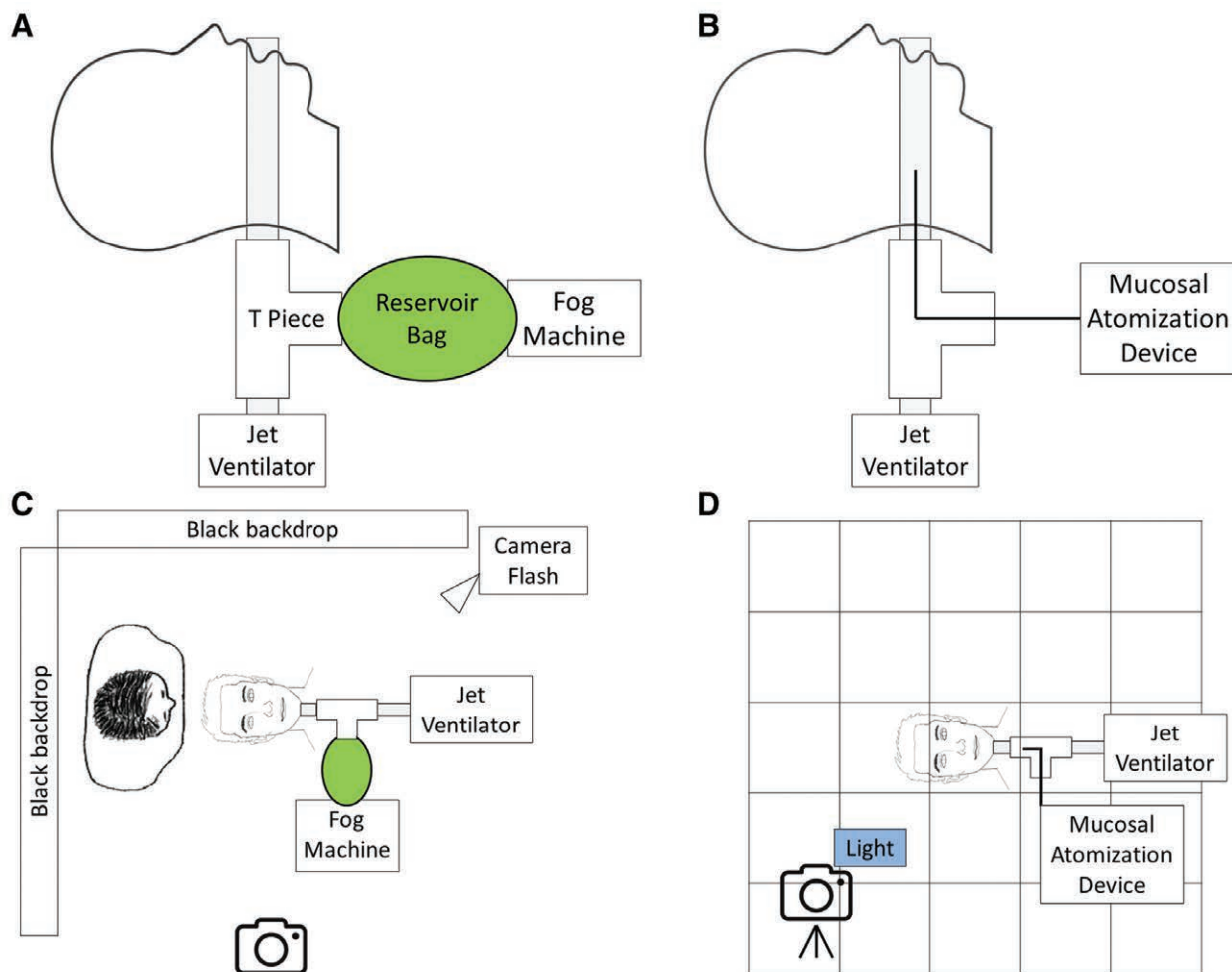


Figure 1. Cough model design, room layout. A, Aerosol generation: cough simulator, mannequin head, reservoir bag, and aerosol generator (fog machine). B, Droplet generation: aerosol generator and reservoir were replaced with droplet generator (MAD connected to syringe). C, Overhead schematic of aerosol setup with cough simulator, fog machine, intubator, camera, and flash. D, Overhead schematic of droplet setup with cough simulator, MAD, and grid. The camera and light were tripod mounted and moved to capture each square individually. MAD indicates mucosal atomization device.

Testing Scenarios

To mimic airway management situations with high potential for infection transmission, we assessed the following scenarios using aerosol and droplet models:

1. Cough simulated without barrier device
2. Cough simulated in 15° of reverse Trendelenburg, without barrier device
3. Cough simulated with intubation box
4. Cough simulated with intubation box, removed after 10 seconds
5. Cough simulated with intubation sheet
6. Cough simulated with intubation sheet, removed after 10 seconds
7. Intubation box filled with fog only^a
8. Intubation sheet filled with fog only^a

^aTo evaluate airflow dynamics with intubation barriers, the fog machine was run continuously for 3 seconds without a simulated cough, which decreased aerosol dilution from the simulated cough.

Each scenario was tested at least 3 times to ensure reproducibility; all trials were inspected, and the authors agreed that the aerosol and droplet spread were consistent within trials for each scenario. Simulator elements were fixed in place, except in scenarios 4 and 6, and the primary variability between trials was cough duration, as coughs were manually triggered. Trials were video recorded for assessment of cough duration, and only those within the target cough durations were used in data analysis. Before testing, all air vents in the testing room were blocked off and doors were closed during experiments to limit confounding airflow.

Data Capture and Analysis

For the aerosol model, high-speed flash photography was used to provide easily understandable, detailed information on cough propagation through time and space (Figure 1C). For the droplet model, the simulator was placed on a fluid-resistant drape and a grid was

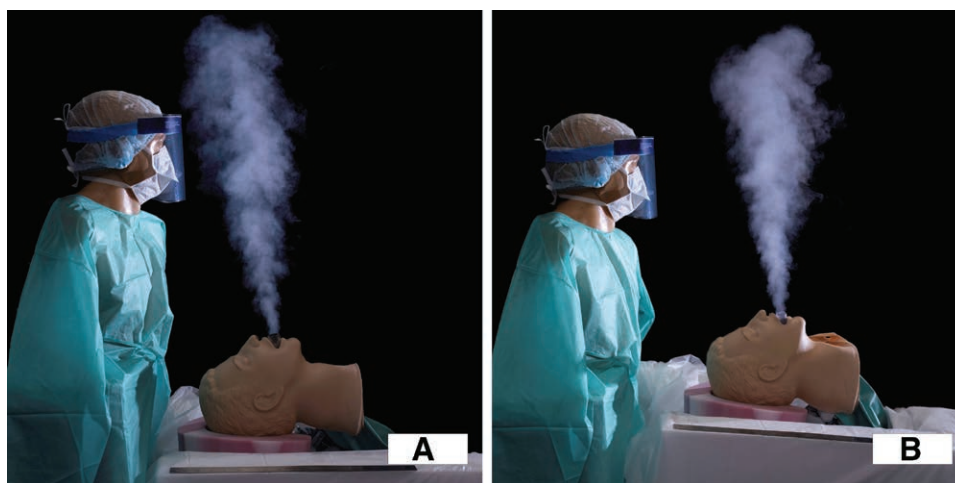


Figure 2. Simulated cough in different positions. A, A representative image taken during a simulated cough of a patient in sniffing position. B, The same patient in 15° of reverse Trendelenburg.

drawn to standardize droplet deposition; exposure to health care workers (HCWs) near the patient was thus inferred (Figure 1D). The cough simulator was placed at the center of the drape and the mannequin head was again placed in sniffing position. Two milliliters of fluorescein dye (1 mg/mL) was rapidly injected through the cough simulator's MAD.^{26,27} A camera and blue light were mounted on a tripod, then used for imaging individual grid locations separately after visual identification of at least 1 droplet in a particular square (Figure 1D). Grid locations were imaged separately to ensure light falloff near the edges of each frame did not negatively impact visual analysis. Scenarios 1, 3, and 5 were repeated in this manner with droplets.

Images were processed in Adobe Photoshop and organized in Adobe Photoshop Lightroom (Adobe Inc, San Jose, CA). Cameras and flashes were triggered remotely while stationary on tripods, with consistent exposure, white balance, and flash intensity. The image processing strategy was similar to that used in digital subtraction angiography, in which the background noise was subtracted using an image of the scene without fog present²⁸ (Figure 2). Visualization of fog beneath the barriers was enhanced through the divide function in Photoshop, which also resulted in an inversion of color (Figure 3). In all images involving fog, the mannequin and cough simulator in the foreground were not altered. Analysis of fluorescein deposition was conducted by separating the green droplets from the blue background by isolating the green channel from the full-color image; photos of different grid locations were then manually aligned and assembled in Photoshop (Figure 4).

RESULTS

Results from scenarios 1 and 2 are seen in Figure 2. The fog was visualized near the intubator's head while the simulator was in standard sniffing position (Figure 2A). When the simulator was placed in 15° of reverse Trendelenburg, fog was directed away from the intubator's head (Figure 2B).

Scenarios including barrier devices are seen in Figure 3. Using the intubation box, fog was seen exiting the box after a simulated cough, with the majority escaping toward the feet. Figure 3C was captured 2 seconds after Figure 3A was captured. In scenarios 4 and 6, a small amount of fog was visible underneath each barrier during its removal. In some instances, the fog was propelled toward the intubator, depending on the manner in which the barrier was removed (Figure 3D–F). When using a 1 × 1 m clear plastic intubation sheet, a small amount of fog was seen escaping toward the intubator (Figure 3G, H). To better visualize this phenomenon and avoid dilution of the fog with the simulated cough, the fog machine was run continuously for 3 seconds under both the intubation box and sheet to track air flow (Figure 3I, J).

Droplet deposition from an uncovered cough, at the level of the patient, is presented in Figure 4A, which shows 3 trials overlaid. Trials involving the intubation box (not pictured) showed droplet deposition within the box, with a minimal amount on the face; no droplets were seen outside the chamber. The intubation sheet also appeared to effectively capture droplets (Figure 4B); however, after its removal, gross contamination was noted on both the sheet and the patient's face (Figure 4C).

DISCUSSION

Barrier devices have been recommended to limit HCWs' exposure during aerosolizing procedures such as intubation and extubation. This study is the first to qualitatively assess these barrier devices with both aerosol and droplet models, using a physiologically accurate cough simulator.

Both intubation boxes and sheets were seemingly capable of capturing droplets in our model, many of which could otherwise have reached the face, neck, and shoes of the HCW. Aerosols were seen escaping both barrier devices during simulated coughs, sometimes directed toward the HCW. Depending on

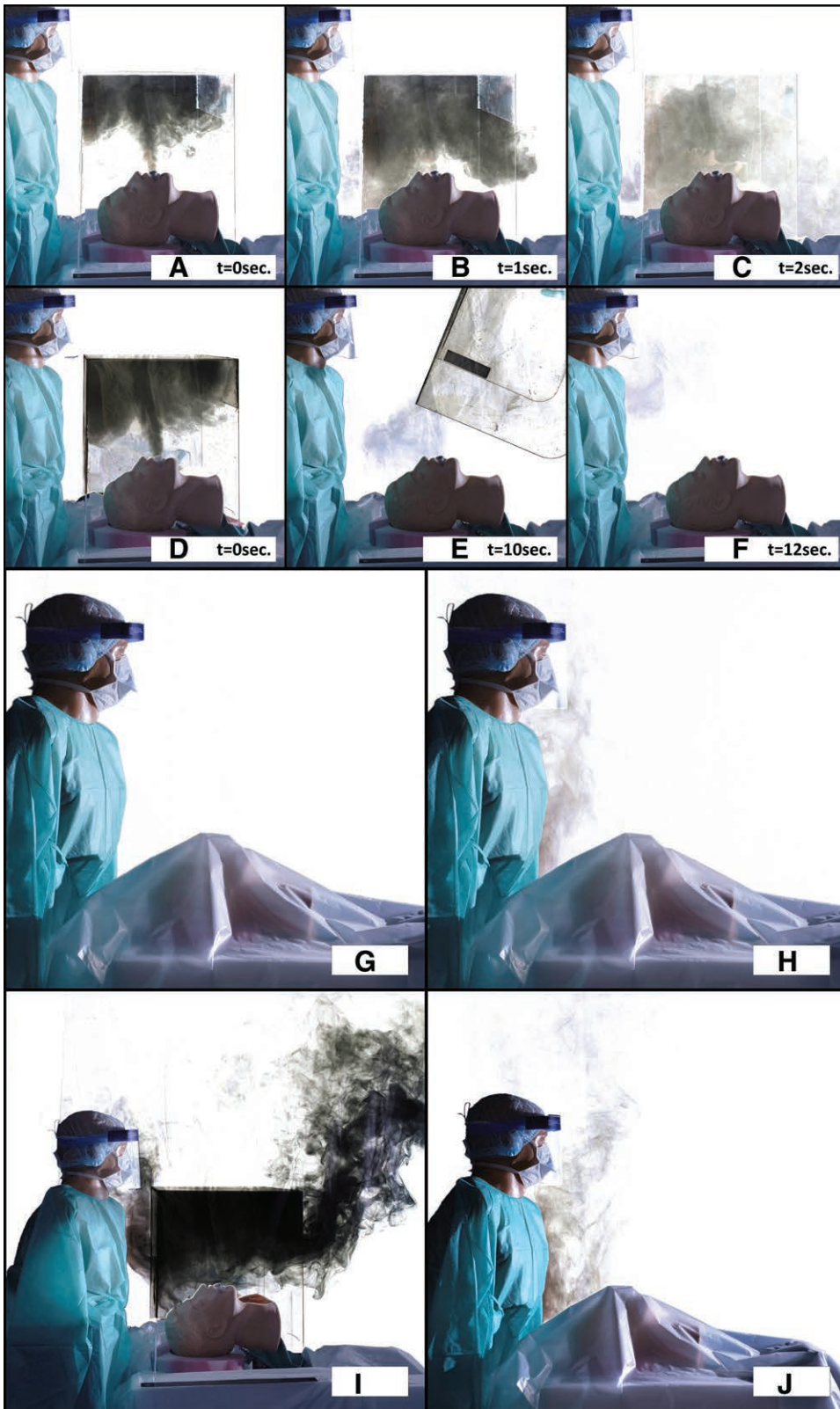


Figure 3. Aerosol spread using barrier devices. A–C, A representative trial of the cough simulator under an intubation box. Fog leaks around the intubation box within the 2 s depicted here. D–F, After simulated cough, the intubation box was removed after 10 s, with fog visibly moving toward the intubator. G and H, A representative trial under an intubation sheet; fog leaks within 7 s after a simulated cough. I and J, To further examine air flow within the barriers, the fog machine was run continuously for 3 s, and in both cases, fog was seen flowing toward the intubator.

how the intubation sheet is draped, it is possible that reaching under the drapes may provide a pathway for warm, rising aerosol to travel toward the HCW. Our model does not allow for visualization of fog beyond

30 seconds after a simulated cough, due to its evaporation; however, our observations suggest that the act of removing these barriers may propel entrained aerosol in an unintended manner, potentially toward

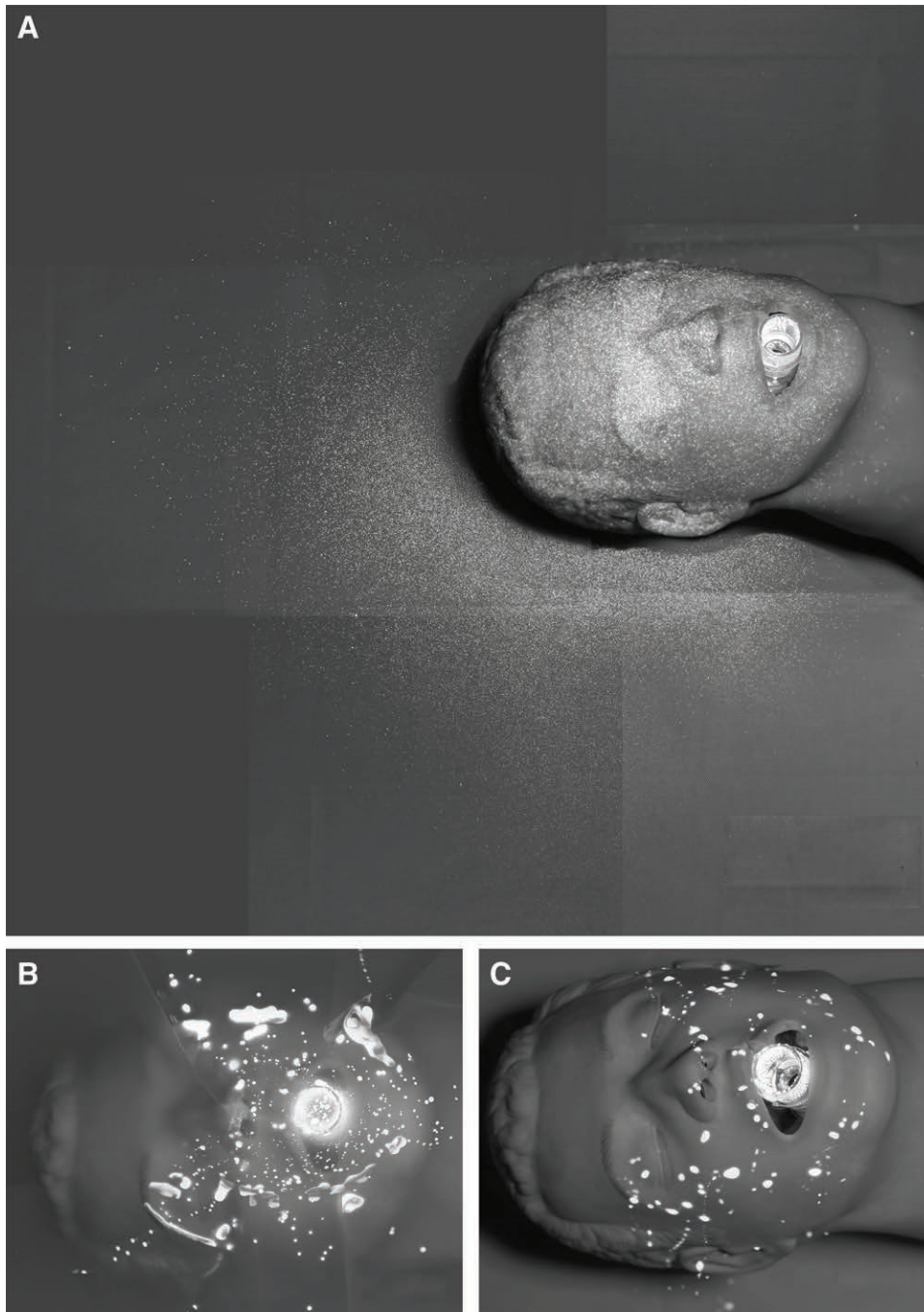


Figure 4. Droplet deposition with cough model. A, Droplet deposition after 3 simulated coughs without a barrier device, using fluorescein. B, Droplets collected on the intubation sheet and mannequin head after 3 trials of simulated coughs, overlaid. C, Residual fluorescein after intubation sheet removal, an overlay of 3 simulated coughs.

the HCW. Furthermore, airflow generated in negative and positive pressure rooms (on the order of 12–20 air exchanges per hour) may be inhibited by these barrier devices, and it is possible that airborne contaminants may continue to disperse over the course of many minutes or even hours.

Patient positioning may have a significant impact on HCW exposure. Optimal intubating conditions include placing the patient's head, neck, and shoulders in sniffing position. However, slight reverse Trendelenburg positioning may redirect aerosol flow away from a HCW standing at the head of the bed.

Although reverse Trendelenburg is not ideal for direct laryngoscopy, video laryngoscopy is currently recommended for COVID-19 patients, and thus this minor change should have minimal impact on intubation time.^{29,30} Given our observation that the intubation box directs more aerosol toward the foot of the bed, it may be prudent for assistants to also stand at the head of the bed to minimize exposure. Finally, our observations suggest that an intubator wearing a forehead-mounted face shield without either neck protection or a powered air-purifying respirator (PAPR) may inadvertently trap aerosol near their face and increase

their risk of exposure. This potential shortfall was also noticed by our clinical intubating team and warrants further investigation.

Due to the urgent need for information during the COVID-19 pandemic, we rapidly developed a cough model that has several limitations. While our cough simulator does not achieve the maximal flow rates of a human cough, it exceeds the average flow rates and is sufficient to propel droplets and aerosols 2.4–2.6 m vertically and horizontally, which approximates a human cough.^{31–33} The simulated cough may even overestimate the strength of a cough in a COVID-19 patient with respiratory decompensation. Although more complex cough simulator designs might afford an increase in fidelity, they come at significant cost and time, while requiring further expertise, which limits the ability of others to replicate our study and test their own protective equipment.

In conclusion, both intubation boxes and sheets may reduce the intubator's exposure to droplets during simulated coughs, but both may merely redirect aerosolized particles, potentially toward HCWs. Patients should be positioned to facilitate intubation, but it is possible that incorporating slight reverse Trendelenburg may direct aerosols away from the intubator. Although barrier devices like the intubation box and sheet were developed to protect HCWs, our observations suggest that these barriers might be ineffective at containing certain infectious particles, and may even increase operator exposure, particularly with aerosolized particles. Further study is necessary to better quantify and investigate the effectiveness of these barrier devices and make way for further innovation. ■

DISCLOSURES

Name: Eric A. Fried, MD.

Contribution: This author helped with study conception, cough model design, data collection, and manuscript preparation, and discussed the results and contributed to the final manuscript.

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Contribution: This author helped with study design, cough model design, data collection, and manuscript preparation, and discussed the results and contributed to the final manuscript.

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