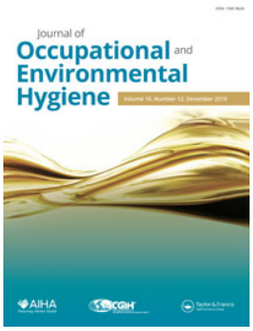

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Efficacy of an ambulance ventilation system in reducing EMS worker exposure to airborne particles from a patient cough aerosol simulator

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ABSTRACT

The protection of emergency medical service (EMS) workers from airborne disease transmission is important during routine transport of patients with infectious respiratory illnesses and would be critical during a pandemic of a disease such as influenza. However, few studies have examined the effectiveness of ambulance ventilation systems at reducing EMS worker exposure to airborne particles (aerosols). In our study, a cough aerosol simulator mimicking a coughing patient with an infectious respiratory illness was placed on a patient cot in an ambulance. The concentration and dispersion of cough aerosol particles were measured for 15 min at locations corresponding to likely positions of an EMS worker treating the patient. Experiments were performed with the patient cot at an angle of 0° (horizontal), 30°, and 60°, and with the ambulance ventilation system set to 0, 5, and 12 air changes/hour (ACH). Our results showed that increasing the air change rate significantly reduced the airborne particle concentration ($p < 0.001$). Increasing the air change rate from 0 to 5 ACH reduced the mean aerosol concentration by 34% (SD = 19%) overall, while increasing it from 0 to 12 ACH reduced the concentration by 68% (SD = 9%). Changing the cot angle also affected the concentration ($p < 0.001$), but the effect was more modest, especially at 5 and 12 ACH. Contrary to our expectations, the aerosol concentrations at the different worker positions were not significantly different ($p < 0.556$). Flow visualization experiments showed that the ventilation system created a recirculation pattern which helped disperse the aerosol particles throughout the compartment, reducing the effectiveness of the system. Our findings indicate that the ambulance ventilation system reduced but did not eliminate worker exposure to infectious aerosol particles. Aerosol exposures were not significantly different at different locations within the compartment, including locations behind and beside the patient. Improved ventilation system designs with smoother and more unidirectional airflows could provide better worker protection.

KEYWORDS

Airborne disease transmission; emergency medical services; emergency vehicle; HVAC infection control; ventilation systems

Introduction

When emergency medical service (EMS) workers transport patients with contagious respiratory diseases in ambulances, the workers can be exposed to airborne particles (aerosols) containing infectious pathogens. Although EMS workers are advised to use airborne precautions when a patient has certain infectious respiratory illnesses,[1] this information about the patient may be unavailable or unclear, and the potential for the airborne transmission of many respiratory infections also is unclear or disputed.[2] In the event of a pandemic of a respiratory illness such as influenza or SARS, ambulances would be used to transport large numbers of infected patients, and EMS workers could receive a high cumulative exposure to infectious bioaerosol particles over the course of their shift. For these reasons, a better understanding of the effectiveness of measures to protect EMS workers against airborne disease transmission is needed.

Several studies have demonstrated the presence of pathogens on various surfaces in ambulances and have examined the risk of the transfer of

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microorganisms to EMS workers (reviewed by Hudson et al.[3]). However, research on the potential for aerosol disease transmission in ambulances has been much more limited. Luksamijarulkul and Pipitsangjan[4] found that concentrations of airborne bacteria and fungi including *Staphylococcus* and *Aspergillus* species were significantly increased during patient transport in ambulances. Bielawska-Drozd et al.[5,6] also found airborne *Staphylococcus*, *Aspergillus*, and *Penicillium* species in ambulances. El Sayed et al.[7] studied reports of occupational health exposures in an urban EMS system and found that the second most common reported exposure was to tuberculosis (17%) while the third most common was to respiratory viral infections (15%).

Ventilation systems play a crucial role in reducing exposure to airborne infectious diseases.[8] However, although a large number of studies have been conducted on ventilation systems and airborne diseases in buildings,[9] studies of ambulance ventilation systems and infectious bioaerosols are far more limited; only one such report was found by us in the scientific literature. Seitz et al.[10] compared an ambulance equipped with a supplemental high-efficiency particulate air (HEPA) filtration system to a standard ambulance by using aerosolized polystyrene microspheres to simulate airborne tuberculosis. They found that the modified ambulance cleared aerosol particles from the air much faster, although they noted that respiratory protection was still recommended when transporting patients with tuberculosis infections.

Guidance and standards for ambulance ventilation rates are also quite limited. Although the 2007 Federal Specification for the Star-of-Life Ambulance called for a ventilation rate of 30 air changes/hour (ACH),[11] this requirement was dropped with a 2008 change order,[12] and the ventilation rate is no longer specified. The current National Fire Protection Association (NFPA) and ASTM International standards for ambulances also do not specify ventilation rates.[13,14] A U.S. Department of Homeland Security guidebook recommends a minimum ventilation rate of 30 ft^3 (0.85 m^3) per minute per person if the enclosure volume is 150 ft^3 (4.25 m^3) or less per person, which would provide 24 ACH if two people were in a 150 ft^3 compartment, but no supporting information is given for this recommendation.[15]

Aerosol particles produced by coughing patients are of particular concern in disease transmission because coughing is one of the most common symptom of respiratory infections and because the violent expulsion of air during a cough generates a plume of aerosol particles that can travel 2 m or more away from an infected person.[16,17] Several studies have shown that people expel aerosol particles containing potentially infectious microorganisms during coughing, speaking, and breathing.[18–22] Small aerosol droplets from a coughing patient can remain airborne for an extended time and can easily be inhaled.[23]

The purpose of this project is to study how an ambulance ventilation system affects EMS worker exposure to airborne particles produced by a coughing patient, and to investigate the effects of the ventilation rate, the position of an EMS worker in the ambulance, and the angle of the patient cot on worker exposure. The results presented here will help inform guidance on protecting EMS workers from airborne biohazards and suggest ways in which protective measures against exposure to bioaerosols can be improved.

Methods

Summary

For our experiments, a cough aerosol simulator mimicking a coughing patient with a contagious respiratory infection was placed on a patient cot in an ambulance (Figure 1). Two sets of experiments were performed. In the first set, aerosol particle monitors were placed at four locations corresponding to likely positions of an EMS worker treating a patient. The simulator coughed an aerosol of KCl particles into the ambulance, and the concentration and dispersion of the aerosol particles were measured for 15 min. Experiments were performed with the patient cot at 0° (horizontal), 30°, and 60°, and with the ambulance ventilation system set to 0, 5, and 12 air changes/hour (ACH). In the second set of experiments, an aerosol containing influenza virus was coughed into the compartment, and bioaerosol samplers were used to collect the particles for 15 min with the patient cot at 30° and the ventilation system set to 0, 5, and 12 ACH.

Ambulance

Our study was conducted using a 2005 Wheeled Coach Type III ambulance (Wheeled Coach, Winter Park, FL) which met the USA Federal Specification KKK-A-1822D when constructed.[24] This specification is very similar to the current construction standards for ambulances that are maintained by the U.S. National Fire Protection Association and ASTM International.[13,14] Type III ambulances represent about half of the U.S. ambulance fleet. The ambulance was located outdoors during testing but was under a

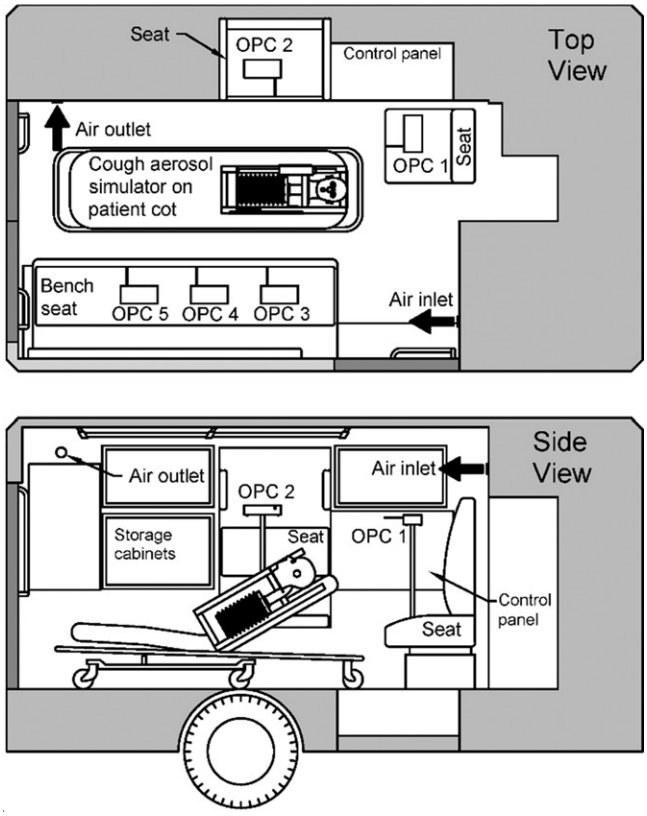

Figure 1. Ambulance patient compartment. The patient cot was adjusted so that the cough simulator was at 0° (horizontal), 30° (as shown in the figure), or 60°. For each test, four optical particle counters (OPCs) were placed in locations representing possible positions for a seated EMS worker treating the patient. OPCs were placed in the positions labeled OPC 1–4 when the cot was at 0° or 30°, and positions OPC 1, 2, 4, and 5 when the cot was at 60°. The inlet of each OPC was placed 70 cm (27 9/16″) above the seat cushion and even with the front of the cushion to place it within the breathing zone of a seated EMS worker. An annotated photograph of the set-up is shown in Figure S4 in the supplemental materials.

carport to avoid direct heating by sunlight. A schematic of the ambulance patient compartment is shown in Figure 1. An annotated photograph of the experimental set-up is shown in Figure S4 in the supplemental materials.

The ambulance patient compartment has three seats for the EMS workers: a rear-facing seat at the head of the patient cot, a seat on the left next to the control panel, and a bench seat along the right side of the compartment (shown in Figure 1 and Figure S4). The aerosol particle monitors and samplers were placed at positions corresponding to the breathing zones of EMS workers sitting on these seats. The position that a worker occupies during patient transport depends upon the tasks they are carrying out, the angle of the front of the patient cot, and the number of EMS workers in the compartment. If the front of the patient cot is raised, the worker may be on the bench seat (positions 3–5) to treat the patient. Position 3 provides good access to the patient's head and torso if the patient cot is flat or at a shallow angle, but the EMS worker may move down the bench seat to Position 4 or 5 when the cot angle is higher. For this reason, in our experiments with the cot angle at 0° or 30°, data were collected at positions 1–4. However, when the cot was at 60°, data were collected at positions 1, 2, 4, and 5.

Ventilation system

The ambulance patient compartment ventilation system consists of an exhaust blower in the rear that draws air from the compartment and vents it outside, an inlet vent in the front that allows outside air to flow into the compartment, and a recirculating heater/cooler to control the air temperature. At maximum speed, the exhaust blower draws 0.7 m^3/min (25 ft^3/min) of outside air into the ambulance. Since the patient compartment has a volume of approximately 8.7 m^3 (308 ft^3), this corresponds to about 5 ACH (the air change rate is the flow rate of air into and out of the compartment divided by the volume of the compartment). The heater/cooler recirculates up to 12 m^3/min of air but does not filter the air, nor does it

exchange inside air for outside air. The heater/cooler was not used in this study.

For our experiments, the exhaust blower was replaced with a recirculating HEPA filtration system (FS4010, Flow Sciences, Leland, NC) connected to the compartment inlet and outlet in order to avoid bringing aerosol particles in from outside of the ambulance and to allow the background aerosol concentration in the ambulance to be reduced to near zero before each experiment. The HEPA filtration system was set to 0 ACH, 5 ACH (matching the original exhaust blower), or 12 ACH (1.8 m^3/min). The current U.S. ambulance standards [13,14] do not specify an air change rate for ambulance patient compartments, but 12 ACH is the recommended ventilation rate for an airborne infection isolation room in a healthcare facility.[25] The air change rates through the HEPA filtration system were measured using an anemometer (VelociCalc Rotating Vane Anemometer 5725, TSI, Shoreview, MN). The 0, 5, and 12 ACH ventilation system air change rates do not include air infiltrating from the outside into the compartment due to natural convention through gaps and seams. Air infiltration was minimized by sealing all exterior doors, windows, and openings leading into the patient compartment with tape or foam. The air infiltration rate into the sealed compartment was measured twice using the tracer gas constant decay method with sulfur hexafluoride as the tracer and the concentration measured using two photoacoustic gas analyzers (Innova Model 1412, Lumasense Technologies, Santa Clara, CA).[26]

Virus and cell stock

Influenza strain A/WS/33 (H1N1, ATCC VR-825) and Madin-Darby canine kidney (MDCK) cells (ATCC CCL-34) were purchased from the American Type Culture Collection (ATCC, Manassas, VA) and maintained as described previously.[27] The influenza virus was propagated in Complete Dulbecco's Modified Eagle Medium (CDMEM) consisting of Dulbecco's Modified Eagle medium, 100 U/mL penicillin G, 100 µg/mL streptomycin, 2 mM L-glutamine, 0.2% bovine serum albumin, and 25mM HEPES buffer (Life Technologies, Grand Island, NY).

Cough aerosols

Our study was conducted using a modified version of the NIOSH cough aerosol simulator described previously.[23,28] The flow rate of the simulated cough was based on cough flow profiles recorded from influenza patients and had a volume of 4.2 L with a peak flow rate of 11 L/sec.[28] The mouth of the cough simulator was 65 cm (25.5 in) above the base of the cough simulator (shown in the supplemental material, Figure S1). The cough aerosol output from the cough simulator was measured using a spray droplet size analyzer (Spraytec Analyzer with an Inhalation Cell, Malvern Instruments Ltd., Malvern, UK) as described previously.[28] A schematic of the cough aerosol simulator and information about the cough aerosol output are shown in the supplemental materials.

For experiments in which the aerosol concentration was monitored using optical aerosol particle counters (OPCs), the cough aerosol was generated by nebulizing a 28% KCl solution using a single-jet Collison nebulizer (BGI, Butler, NJ) at 14 kPa (20 lb/in^2), passing the aerosol through a diffusion drier (Model 3062, TSI, Shoreview, MN), and mixing it with 8.1 L/min of dry filtered air. Aerosol particle concentrations were measured using optical aerosol particle counters (OPCs; Model 1.108, GRIMM Technologies, Douglasville, GA). The OPCs were controlled by a laptop computer running a custom-written LabVIEW program (National Instruments, Austin, Texas) through a wireless RS-232 interface (Parani SD1000 and UD100, Sena Technologies, Seoul, Korea). The GRIMMs were programed to report particle counts/liter in eight size bins from 0.3–3 µm at a rate of once per second.

For experiments using influenza virus, the virus was diluted in modified Hank's Balanced Salt Solution (MHBSS), which consists of HBSS supplemented with 0.1% bovine serum albumin (BSA) (Sigma–Aldrich, St. Louis, MO), 100 units/mL penicillin G and 100 units/mL streptomycin (Invitrogen, Carlsbad, CA). The nebulizer solution had a viral concentration of 4.46 x 10^7 viral copies/mL. The cough aerosol was generated by nebulizing the virus solution using a micropump nebulizer (Aeroneb AG-AL7000SM, Aerogen, Chicago, IL). The virus aerosol was mixed with 2 L/min of dry filtered air, passed through the diffusion drier, and mixed with an additional 7 L/min of dry filtered air. The viral aerosols were collected in the patient compartment using bioaerosol samplers (BioSampler, SKC, Eighty-four, PA). The flowrate through the SKC BioSamplers is controlled by three critical orifices. The mean flowrate through our set of BioSamplers is 13.2 L/min (standard deviation 0.62). The vacuum for each sampler was supplied by a Gast DOA-P704 vacuum pump (Gast Manufacturing, Benton Harbor, MI).

Test procedure

Two types of experiments were performed: Measurements of the aerosol particle volume concentration over time, and collection of airborne influenza virus.

For the aerosol volume concentration measurements, the cot angle was set to 0°, 30°, or 60°. For experiments with the patient cot at 0° or 30°, optical aerosol particle counters were placed in positions 1–4, as shown in Figure 1. For experiments with the cot at 60°, the OPCs were placed in positions 1, 2, 4, and 5 in order to include a location further down the bench seat where an EMS worker might be when the patient is more upright. The cough simulator nebulizer was loaded with 28% KCl. The HEPA system was run at its maximum rate to reduce the aerosol concentration as much as possible, and a fan was used to increase air mixing. After 45 min, the fan was turned off and the HEPA system was set to the rate to be used in the experiment (0, 5 or 12 ACH). The air movement in the compartment was allowed to stabilize for 10 min, during which time the OPCs measured background concentration levels. The cough aerosol simulator then coughed once into the compartment. After each cough from the simulator, the number concentrations of aerosol particles with optical diameters from 0.3 to 3 μm were measured for 15 min at 1 Hz using the OPCs. The number concentrations were converted to volume concentrations as described below. Four replicate experiments were conducted for each combination of cot angle and ventilation rate (36 experiments total). Within the experimental replicates, the four OPCs were rotated among the four positions so that each OPC was in each position once.

For experiments with airborne influenza virus, the procedure was similar, but the OPCs in positions 1 and 4 were replaced with BioSamplers containing 20 mL of MHBSS. The HEPA system and fan were run for 30 min and then the air movement was allowed to stabilize for 10 min before coughing. The BioSamplers were started a few minutes before the simulator coughed, and aerosol collection continued for 15 min after each cough. After the aerosol collection was completed, the bioaerosol collection was stopped and the HEPA system and fan were run for 30 min to clear the airborne virus in the compartment before the bioaerosol samples were retrieved. Experiments were conducted with the HEPA system at 0, 5, and 12 ACH and with the cot at 30° only. Three replicates were conducted for each air change rate for a total of nine experiments.

Influenza virus RNA isolation and qPCR detection

Viral RNA was isolated from the collected aerosol samples using the MagMAX™ Viral RNA Isolation kit (Thermo Fisher Scientific, Waltham, MA, USA) as described by Blachere et al.[29] In brief, 1 mL (5%) of the collected aerosol sample was supplemented with a 1:1 volume of 2-propanol (Sigma). The manufacturer's instructions were followed for the remainder of the viral RNA isolation procedure. Viral RNA was eluted with 30 μL of elution buffer and transcribed into cDNA using the High Capacity cDNA Reverse Transcription Kit (Thermo Fisher Scientific).

Molecular analysis of viral-laden cough aerosols was performed using quantitative polymerase chain reaction (qPCR) targeting the matrix 1 (M1) gene of influenza strain A/WS/33, as previously described.[29] A 5 μL (12.5%) cDNA volume was analyzed per sample, in duplicate.

Data analysis

When fluids such as lung secretions are aerosolized, the number of pathogens that an aerosol particle can carry depends upon the volume of the particle; larger particles can carry more pathogens. As a result, the aerosol volume concentration (total volume of aerosol particles per unit volume of air) gives a better indication of the amount of airborne infectious material to which a worker is potentially exposed than does the number concentration (total number of aerosol particles per unit volume of air).[30–32] For this reason, the aerosol concentration data reported in this article are in volume concentration. The volume concentration is analogous to the more commonly used mass concentration; if the aerosol particles have a constant density, the mass concentration is simply the volume concentration multiplied by the density of the particles. A more detailed explanation of the volume concentration is provided in the supplemental materials.

The optical particle counters report the number of aerosol particles detected per liter of air (#/L) in eight logarithmically spaced size bins from 0.3–3 μm. The background aerosol number concentration was calculated based on the mean number concentration in each size bin during the 3 min before the cough and was subtracted from the concentrations measured after the cough. The volume of the aerosol in each size bin per m^3 of air (volume concentration) was calculated by multiplying the particle count by the volume of an individual particle with the mean diameter of the size bin, assuming the particles were spherical. The total aerosol volume/m^3 (total aerosol volume

concentration) was found by summing the aerosol volume concentrations for all the size bins. The mean volume concentration was found by averaging the total volume concentration over 15 min starting from the time of the cough.

The total volume of aerosol expelled by the cough aerosol simulator changes with the cot angle (shown in the supplemental material, Table S1), although the size distribution does not change noticeably. The output at 0° is about 7% higher compared to 30°, while the output at 60° is 14% lower. To control for this variation in output, the volume concentrations at 0° and 60° were normalized to the 30° concentrations by dividing them by a normalization factor:

$$\textit{Normalization factor} = \frac{\textit{cough aerosol output at experiment cot angle}}{\textit{cough aerosol output at } 30^\circ \textit{ cot angle}} \quad (1)$$

In the "Results" section, "concentration" always refers to the normalized volume concentrations.

Due to the skewed nature of the concentration data, a natural logarithm transformation was performed prior to the analysis. Because measurements were made at positions 1, 2, 3, and 4 when the cot angle was 0° or 30° and at positions 1, 2, 4, and 5 when the cot angle was 60°, an initial analysis of the overall effect of position on mean volume concentration was performed, which showed that the position did not have a significant effect. Following this, a two-factor factorial design was used to examine the effects of the angle of the patient cot (three levels: 0°, 30°, or 60°), air exchange rate (three levels: 0, 5, or 12) and their interaction at each position. If significant differences were found, Tukey's multiple comparison test was used to determine which means were significantly different from the rest. All possible multiple comparison tests were performed for each combination of cot angle (0°, 30°, and 60°) and air change rate (0, 5, and 12 ACH). The data were analyzed using SAS (Version 9.4, SAS Institute, Inc., Cary, NC). The SAS analysis of the results is shown in the Supplemental materials.

Supplemental online material

A supplemental file for this article is available online. It includes a schematic of the cough simulator, an annotated photograph of the experimental set-up, additional graphs and explanatory material, a table providing the experimental data, and the SAS output.

Results

Cough aerosol volume concentration over time

The aerosol volume concentrations over time at position 1 are shown for the 30° cot angles in Figure 2. At 0 air changes/hour, the aerosol concentration tended to level off after a few minutes, while the concentration declined over time at 5 ACH and declined more rapidly at 12 ACH. Results for all positions and cot angles are shown in the supplemental material. Some differences can be seen at different cot angles for 0 ACH, but the concentration curves are fairly similar at the different cot angles for 5 ACH and 12 ACH.

Mean aerosol volume concentration

The mean aerosol volume concentrations over the 15-min test interval are shown in Figure 3 for each position, cot angle and air change rate. Changes in the air change rate had a significant effect on the aerosol concentration ($p < 0.0001$). For example, at position 1 with the cot at 0°, the mean aerosol concentration at 5 ACH was 64% (standard deviation, SD = 10%) of the 0 ACH concentration, and at 12 ACH the mean concentration was 32% (SD = 5.4%) of the 0 ACH value. The air change rate had similar effects at the other positions and cot angles. Overall, for all positions and angles combined, the 5 ACH flowrate reduced the mean concentration to 66% (SD = 19%) of the 0 ACH value, while 12 ACH reduced the mean concentration to 34% (SD = 9.3%) of the 0 ACH level. The aerosol volume concentrations also were affected by changes in the cot angle ($p < 0.0001$), although the effects were more modest, especially at 5 and 12 ACH. For example, at position 4 with 0 ACH, the concentration with the cot at 30° increased to 128% (SD = 28%) of the concentration at a 0° angle, while the concentration with the cot at 60° decreased to 75% (SD = 11%) of the 0° level. On the other hand, the position of the particle counter in the patient compartment did not have a significant effect on the concentration ($p = 0.556$). For example, at a 30° cot angle with 12 ACH, the mean concentrations at positions 2, 3, and 4 were 95% (SD = 11%), 95% (SD = 13%), and 93% (SD = 7.3%) of the position 1 concentration. The statistical interaction between ACH and cot angle was significant ($p = 0.0031$ for position 1, $p < 0.0001$ for positions 2 and 4). Graphs showing the data with different groupings of bars are shown in the supplemental materials.

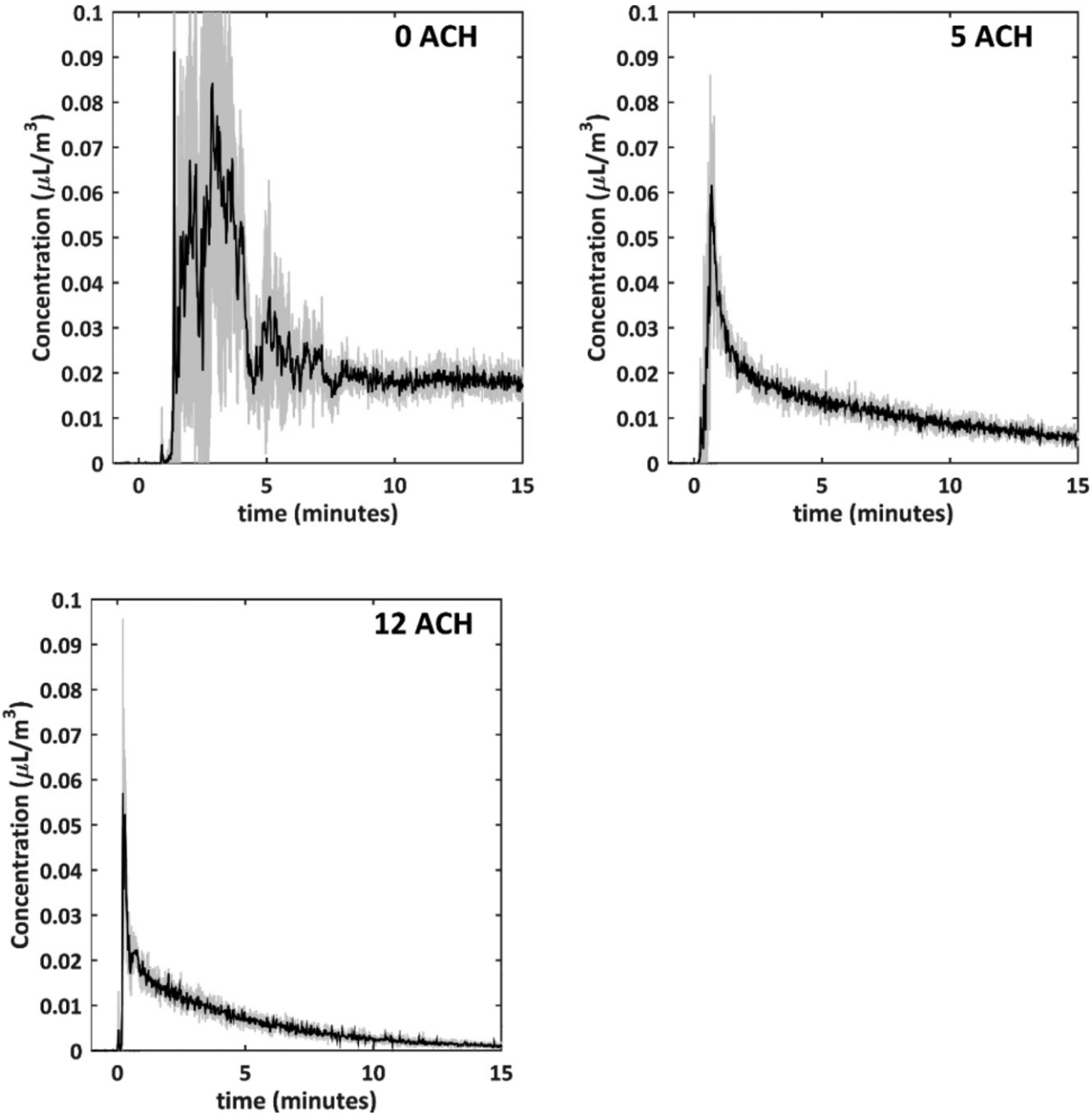

Figure 2. Aerosol volume concentration over time at position 1 with the cot at 30° at air change rates of 0, 5, and 12 ACH. The aerosol volume concentration is the total volume of KCl aerosol particles from 0.3–3 μm in diameter per m^3 of air. Each line is the mean of four experiments. The gray shading shows the standard deviation.

Exposure to airborne influenza virus

The cough aerosol simulator was used to cough an aerosol containing influenza virus into the patient compartment, and the viral aerosol was collected for 15 min at positions 1 and 4. The amount of airborne virus detected (viral M1 copies/m^3 of air) is shown in Figure 4. Similar to the results seen in Figure 3, the air change rate had a significant effect on the amount of airborne virus ($p = 0.0001$), while the two positions were not significantly different ($p = 0.850$). In position 1, the amounts of airborne virus at 5 ACH and 12 ACH were 71% (SD = 21%) and 43% (SD = 7.0%) of the 0 ACH value, while in position 4 they were 60% (SD = 30%) and 29% (SD = 10%)

Environmental conditions

For the experiments using KCl aerosols, the overall mean temperature inside the patient compartment was 26 °C (SD = 2.1) and the mean relative humidity

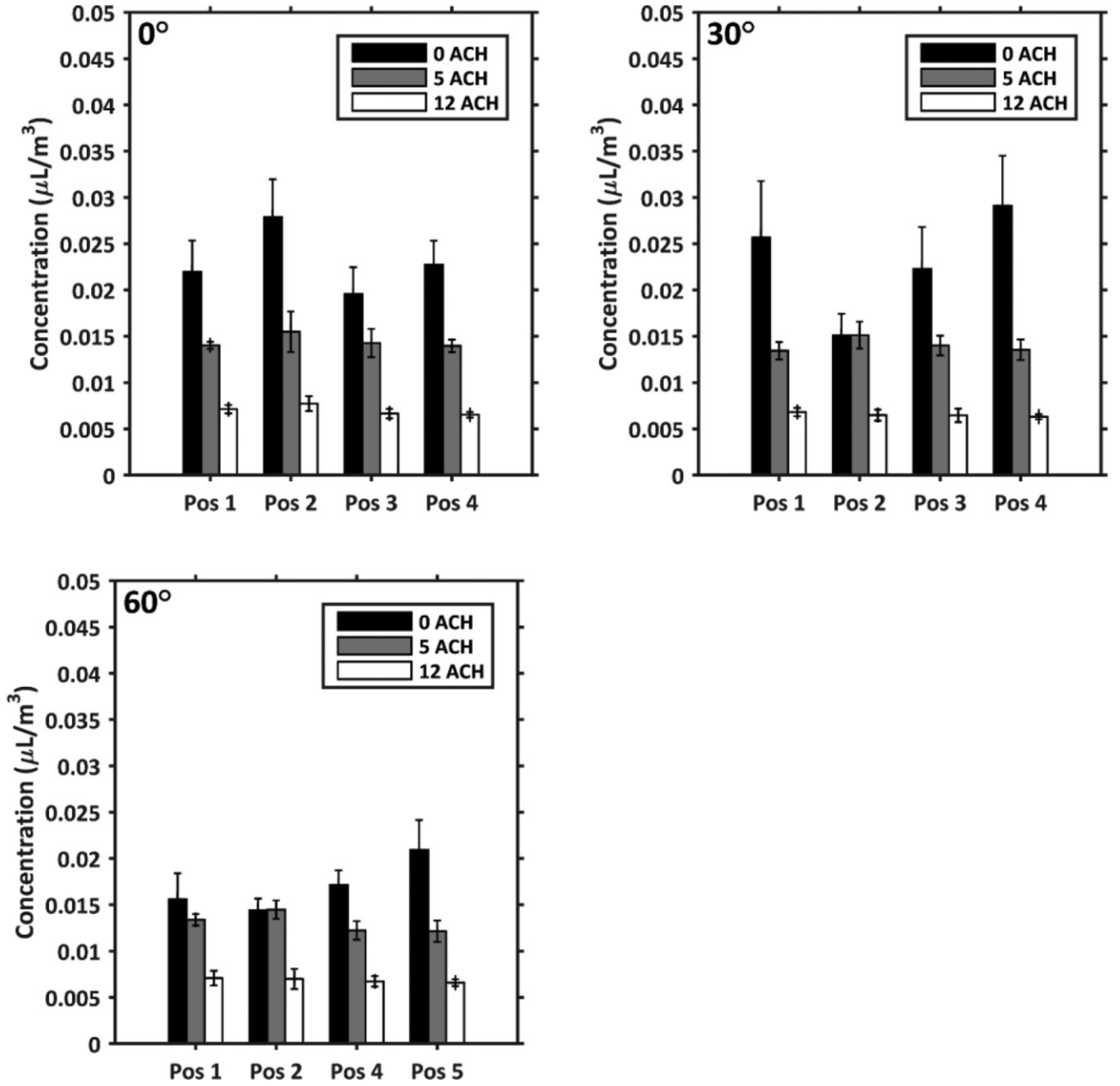

Figure 3. Mean aerosol particle volume concentration over 15 min at each position and air change rate with the cot at 0°, 30°, and 60°. Each bar shows the mean and standard deviation of four experiments using 28% KCl. The air change rate and cot angle had a significant effect on the mean concentrations ($p < 0.0001$ for both), while results at different positions were not significantly different ($p = 0.556$).

was 60% (SD = 5.4). For the influenza virus experiments, the mean interior temperature was 26 °C (SD = 1.9) and the mean humidity was 67% (SD = 2.5). The air infiltration rate into the sealed compartment was 0.26 ACH (SD 0.04; n = 2) with the ventilation system off.

Discussion

EMS workers transport patients with a variety of infectious diseases, including some that can be spread by airborne particles. Patients are typically in an EMS transport vehicle for a relatively short time; in the U.S., average ambulance transport times are 11 min in urban and suburban regions and 17 min in rural areas.[33] However, even a short exposure to a high concentration of an infectious bioaerosol can result in infection, and longer transport times are not uncommon. In addition, during a respiratory disease pandemic, workers would be transporting multiple infected patients to health care facilities over the course of their shift, and their cumulative exposures

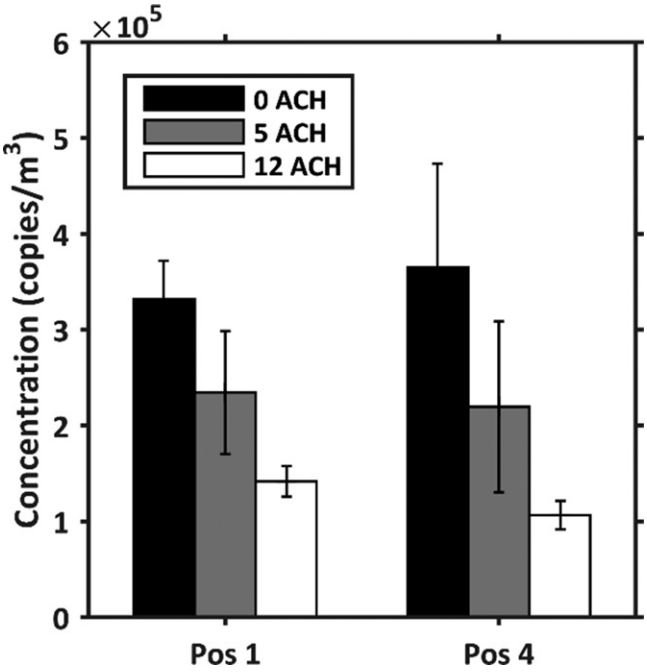

Figure 4. Airborne influenza virus concentration in viral M1 copies/m^3 of air. Airborne virus was collected for 15 min after each cough. The patient cot was at a 30° angle. Each bar shows the mean and standard deviation of three experiments. The air change rate had a significant effect on the mean concentration ($p < 0.0001$), while the OPC position did not ($p = 0.850$).

could be substantial. The use of ventilation to reduce exposure to airborne contaminants in buildings has been widely studied, but in ambulances such studies have been far more limited. Although the same principles apply to both settings, ambulances are cramped spaces with much less air volume per person than a typical patient room in a medical facility, which greatly increases the potential exposure to infectious aerosols. In addition, ambulances have ventilation systems that are quite different from hospital rooms. Thus, ventilation studies need to be done specifically in ambulances in order to understand the risks to EMS workers and the effects of different parameters such as worker location, patient position, ventilation rate, and the effectiveness of ventilation designs to use dilution and directed airflows to protect against worker exposures.

As can be seen in Figure 2, when a patient coughs into the ambulance compartment, the cough results in a rapid initial increase in the aerosol particle volume concentration. With no mechanical ventilation, the aerosol concentration levels off after a few minutes, while the concentration gradually declines at 5 ACH and declines more rapidly at 12 ACH. Thus, the ventilation system does reduce exposure to bioaerosols, but only gradually over time, and some worker exposure is unavoidable. This can also be seen in Figure 3, which shows the aerosol volume concentration averaged over 15 min. The ventilation system clearly reduces the exposure to bioaerosols, and the reduction is more rapid at a higher ventilation rate, but significant worker exposure still occurs in every position. It should also be noted that the experiments presented here tracked the aerosol concentration after a single cough; if a patient were coughing every few minutes or was exhaling airborne pathogens, as is common, the bioaerosol content of the compartment would be constantly renewed and the mean concentrations would be higher.

Contrary to our expectations, Figure 3 also shows that while the mean aerosol volume concentrations were somewhat different at the different worker locations in the ambulance at 0 ACH, the mean concentrations at 5 ACH and 12 ACH were very similar from position to position. Similarly, at 0 ACH, the aerosol concentrations were lower at each position with the cot at 60° compared to 0° or 30°, presumably because when the simulator was more upright, the cough was directed more toward the rear of the ambulance. However, when the air change rate was 5 ACH or 12 ACH, changing the cot angle had only a small effect on the mean aerosol concentrations. These outcomes can also be seen in Figure 4; tests using an influenza virus aerosol showed that increasing the air change rate to 5 and 12 ACH significantly reduced the amount of virus collected at positions 1 and 4, but at each air change rate there was no significant difference between the two positions.

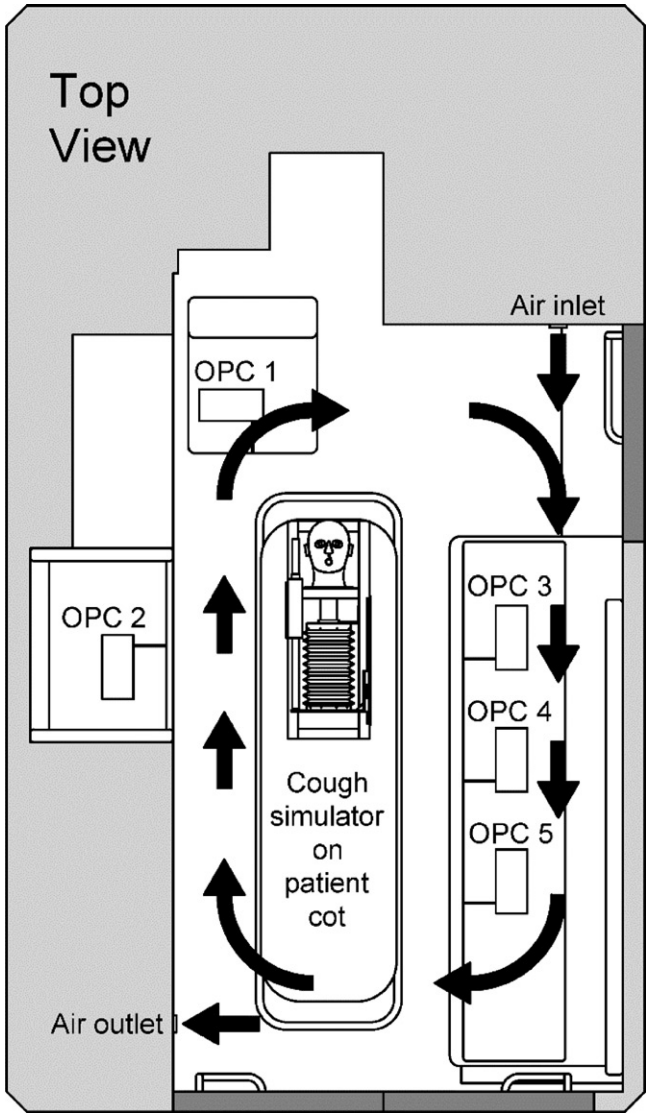

Figure 5. Air circulation pattern in the ambulance patient compartment generated by the ventilation system. The jet of air created by the air inlet causes a clockwise recirculation pattern to form which circulates aerosol particles throughout the compartment. Even if the cough is directed toward the rear of the ambulance, aerosol particles are carried toward the front by the recirculation. Thus, a worker anywhere in the ambulance is exposed to the cough aerosol particles.

These results seemed counter-intuitive; we anticipated that the worker positions at the head of the patient cot would receive lower aerosol concentrations, especially as the cot angle increased and the cough was directed more toward the rear of the ambulance. However, an investigation using smoke visualization of the airflow patterns in the patient compartment revealed that, because the airflows into the ambulance from a small inlet on the right-hand side at the front (Figure 1), the air forms a jet along the right side that generates a clockwise recirculation pattern (Figure 5) spanning the compartment. This recirculation carried air from the rear of the ambulance along the left side and toward the front of the compartment, sweeping aerosol particles from the back toward the front of the ambulance. Thus, the air mixing caused by the cough itself and the circulation pattern created by the ventilation system caused a high degree of air mixing and quickly distributed the cough aerosol throughout the compartment. This effect can be seen in Figure 2. In position 1, with the cot at 30°, the aerosol concentration peaks earlier after the cough as the airflow rate increases to 5 ACH, and even earlier at 12 ACH. The earlier peaks indicate that the aerosol is being carried more rapidly from the rear of the ambulance toward the front as the airflow increases.

This observation provides an important lesson for designing ambulance ventilation systems to reduce aerosol exposure: It is not sufficient to simply blow air into a patient compartment at the chosen air

change rate. The airflow patterns need to be analyzed and the ventilation system designed so that the air is swept away from the patient and worker and toward an outlet. For example, a laminar airflow system with air entering from a broad inlet in the ceiling and exiting at the floor could be used to quickly sweep particles downward below the breathing zone of the worker while avoiding air mixing or recirculation. Alternatively, it may be possible to design a laminar flow system with air flowing from the front to the back of the ambulance, although this could be problematic if the worker needs to be downstream of the patient. Vertical and horizontal laminar airflow systems are now used in operating rooms to prevent contamination of surgical sites by airborne particles settling into wounds.[34] Similar concepts could potentially be applied to ambulances to reduce the inhalation exposure of workers to airborne pathogens, although ambulances have significant space constraints compared to buildings. It should be emphasized that any new ventilation system will need to be carefully tested and evaluated to ensure that it is actually providing the needed protection from bioaerosols.

Finally, the limitations of our study need to be acknowledged. First, the optical particle counters measured airborne particles from 0.3–3 μm, which covers many of the bioaerosol particles that are small enough to remain airborne for an extended time but large enough to carry pathogens. However, humans do produce aerosol particles across a very broad size range that carry pathogens,[35] and particles outside our test size range would behave differently. Second, the cough aerosol simulator and the particle counters are at ambient temperature, not body temperature, and thus do not create the thermal convection currents that people would generate. Third, the conversion from particle counts to particle volume used to analyze our data is commonly used but should be regarded as an approximation. Fourth, the particle counters and aerosol samplers were kept in fixed locations during our experiments, while EMS workers may move during patient transport, which could affect particle movement and the worker's exposure. Finally, our ambulance was stationary during our tests and all openings to the exterior were sealed; thus, any additional ventilation effects that would occur due to air infiltration into a moving ambulance were not included in our study.

Conclusions

The protection of EMS workers from airborne disease transmission is important during routine transport of patients with infectious respiratory illnesses and would be critical during a respiratory disease pandemic. Thus, a better understanding of exposure control devices such as ambulance ventilation systems is needed. Our results show that an ambulance ventilation system does reduce EMS worker exposure to infectious aerosol particles produced by patients, but the systems may still allow significant exposure to occur even at relatively high air change rates. Our results also indicate that aerosol exposure can occur at all locations within the compartment, and that locations behind or beside the patient cannot be assumed to be safe from airborne particles. Finally, our results suggest that improved ventilation system designs with smoother and more unidirectional airflows could provide better worker protection.

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